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Attention allocation patterns in naturalistic driving

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ABSTRACT

The key to safe driving is the adequate distribution of the driver's attention to the forward area and to other non-forward focal points. However, thus far, current methods are not able to well quantify the entire process of a driver's attention allocation. Therefore, this study proposed a novel concept of renewal cycles for representing and analyzing driver attention allocation. Using the 100-car naturalistic glance data, this study found that 90.74% of drivers' attention allocations were 2-glance renewal cycles. The findings suggest that the sample drivers usually separated their lapses of attention from the forward direction into several sequences by directing their vision back to the forward direction after each visual shift away from it. In addition, although a markedly smaller number of cycles were more than 3-glances (2.09% renewal cycles), drivers were certainly less aware of the frontal area and at a higher risk of having an accident during such cycles. This finding might have striking implications for accident prevention. This area of study deserves further attention. Among the generated renewal cycles, lots of them repeated frequently, especially cycles related to invehicle distractions. To analyze the different characteristics among various attributes, distribution of the common renewal cycles under different conditions was examined. As expected, drivers displayed different renewal cycles under various road conditions and with various driver intentions. Although these sample drivers were not representative, the preliminary research results were promising and fruitful for potential applications, particularly educating novice drivers.

1. Introduction

Exploring the causes of motor vehicle crashes has become a pressing issue. The majority of crashes are considered preventable, provided that the surrounding area is properly observed by the driver and adequate maneuvers are successfully executed (Wong et al., 2010). Presumably, misallocating attention is one of the most critical contributing factors in crashes (Brown et al., 2000; Mcknight and Mcknight, 2003; Underwood et al., 2003; Underwood, 2007; Di Stasi et al., 2009; Olson et al., 2009; Chan et al., 2010). It inhibits the driver's ability to perceive information adequately and increases the likelihood of a crash. Thus, understanding the patterns of attention allocation is crucial to analyzing the relationship between crashes and ways to maintain situational awareness through visual transition.

Safe driving requires the driver to pay continued attention to various areas and to constantly update awareness of the driving environment. Locations or objects do not attract drivers' attention randomly; specific patterns draw a driver's visual field. In general, before implementing maneuvering intentions, drivers tend to look in the direction of future vehicle trajectories, i.e., where they expect the greatest number of threats to occur (Salvucci and Liu, 2002; Underwood et al., 2002, 2003; Nabatilan, 2007; Underwood, 2007; Levin et al., 2009). For instance, moving forward constitutes a major driving activity. Hence, the frontal area attracts the most attention in almost all driving conditions (Underwood et al., 2003; Nabatilan, 2007; Underwood, 2007; Levin et al., 2009). Changing lanes requires heightened attention to be invested in the adjacent lane (Salvucci and Liu, 2002; Underwood et al., 2003). Entering an intersection compels drivers to look to both sides of the intersected roads (Summala et al., 1996). In addition to the attention required for specific intended maneuvers, drivers allocate attention to surrounding areas to maintain awareness of traffic conditions and to prevent possible conflicts caused by other vehicles (Crundall et al., 2006).

In other words, the key to safe driving is the adequate distribution of the driver's attention both to the forward area and to other non-forward focal points. Shifting attention away from the frontal area invites a possible lack of awareness of traffic conditions ahead and increases the unawareness of safety considerations (Brown et al., 2000). Klauer et al. (2006) stated that shifting vision away from the forward area longer than 2 s increases the

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crash/near-crash risk by at least twofold. By contrast, focusing only on the frontal area limits the driver's awareness of the surrounding traffic and the time to react to sudden dangers. Knowledge of the patterns in which drivers allocate visual attention between frontal and surrounding areas provides insight into the information-seeking behavior of drivers and its relationship to safety. To investigate these attention allocation patterns, we posed the following four questions: (1) How should the patterns be represented? (2) Do patterns drivers commonly adopt occur? (3) If so, what are the patterns? (4) What factors contribute to the patterns?

Before analyzing the contribution of specific attributes to attention allocation, an appropriate method for representing attention allocation must be identified. Therefore, this study investigated (1) methods for representing attention allocation patterns, and (2) the occurrence of actual representative patterns of the available sample of drivers from the 100-car event database.

2. Methods for analyzing attention allocation

2.1. Current practiced methods

Driver attention is not a manifest variable that can be measured directly. Thus, developing an appropriate representation of attention allocation is challenging. Nevertheless, various representations have been provided to analyze several aspects of attention allocation.

One method entails representing attention allocation by using a single focal point. The duration and frequency of drivers transiting their visual fields to a specific direction have been intensively studied. The results have shown that the portion of time that drivers spend looking at particular objects or areas is usually related to the importance of the areas (Underwood et al., 2003; Nabatilan, 2007; Levin et al., 2009; Borowsky et al., 2010; Konstantopoulos et al., 2010). Longer glances are more likely directed to the areas of a driver's highest safety interest. In addition, frequent saccades usually occur when a driver quickly gathers information under mentally demanding conditions.

Because presenting the process of drivers transiting visual fields among various focal points is not practical by employing the single-point approach, some studies have used scan paths to represent attention allocation (Underwood et al., 2003; Wong and Huang, 2011). The scan path method examines multiple and sequential focal points to which drivers divert their glance. This method explores the detailed behavior of drivers shifting attention from one focal point to another. By extracting the scan path, it provides additional information on drivers' sequential processes of attention allocation for maintaining situational awareness.

However, results from the aggregated scan paths have contained only two or three sequential points and have shown that the most common paths were heading toward or shifting away from the frontal area. The forward area, as the most attractive focal point, dominates the process of attention allocation. Using the aggregated scan path method may obscure the characteristics of other non-forward focal points. Also, the scan path method does not account for glance durations. Drivers can transit their vision along an identical path at either a slow or a rapid pace. For example, an identical path of shifting attention from the forward direction to the rear-view mirror can be derived either from a lengthy glance at each focal point or from repeatedly and rapidly transiting vision between the two. The similarity in scan paths does not imply equivalent attention-allocation patterns or strategies.

In addition, connecting the related scan paths together may offer rigorous meanings that correlate to the associated driving activities. Examining the deeper characteristics of such paths facilitates understanding of the behavioral patterns of drivers allocating attention in various conditions. Therefore, to analyze the whole process of attention allocation, a new method is needed.

2.2. The proposed renewal cycle approach

To describe the complete process of attention allocation more clearly, this study expanded the concept of the scan path to analyze attention allocation using *renewal cycles*. A *renewal cycle* represents the process of shifting vision from a reference point, transiting to other points, then shifting back to the reference point. Identifying a renewal cycle requires determining its beginning and ending points. Moving forward is a major activity of driving; thus, this study regarded the forward area as the focal point at which drivers look naturally and comfortably. The forward area is also the point to which drivers eventually return their attention after shifting it away. Therefore, using "forward" as the initial reference point, this study defined a renewal cycle as the driver directing his or her attention forward, transiting to other focal points, and then returning the gaze again to the forward area.

This approach not only distinguishes on- and off-road glances but also represents a complete chain process of the driver shifting attention from one point to another and transiting their vision back to the front. Using the renewal cycle as the basic component of attention allocation facilitates in-depth exploration of drivers' visual transition characteristics among focal points, especially the transition among non-forward focal points. In addition to the extracted paths transiting toward or from the forward area, this method enables the inclusion of additional serial focal points as a pattern to reflect the entire process of drivers allocating their attention during certain tasks or events. Analyzing renewal cycles can help clarify the interactions between forward and non-forward glances. For instance, drivers employing different strategies of attention allocation by varying the durations of forward and non-forward glances in one renewal cycle may indicate their various ways of searching information.

2.3. The research framework

Fig. 1 shows the research framework for analyzing attention allocation from a renewal cycle perspective.

We first processed the glance data that recorded every 0.1 s into glances for each specific focal point. Then the glances were grouped into renewal cycles anchored by forward glances. The purpose of generating renewal cycles was to generate the basic component of the attention allocation patterns. However, not all of the cycles were equally important. We evaluated the importance of each cycle to identify the minimum number of commonly used renewal cycles that explain the majority of attention allocation processes. The indicator of importance adopted was the recurring frequency of a renewal cycle. If a specific type of renewal cycle occurred more frequently than others, it was considered a crucial cycle typically employed by drivers. Then, characteristics of renewal cycles by attributes were analyzed.

Among the generated renewal cycles, several identical cycles were undertaken by drivers repeatedly before beginning another renewal cycle. This repetitious behavior is probably intended to prevent the risk caused by long glances away from the forward area by transiting vision back and forth between the road ahead and the non-forward focal point. Repeated renewal cycles likely result from the intention to complete an activity or continual monitoring of potential dangerous threats. To gain deep insight, these repetitious behaviors are bundled as a repeated renewal cycle.

Further grouping of the renewal cycles helps elucidate the associated driving activities. After the common renewal cycles were identified, this study charted the regular patterns of attention allocation by combining the renewal cycles that usually occur jointly.

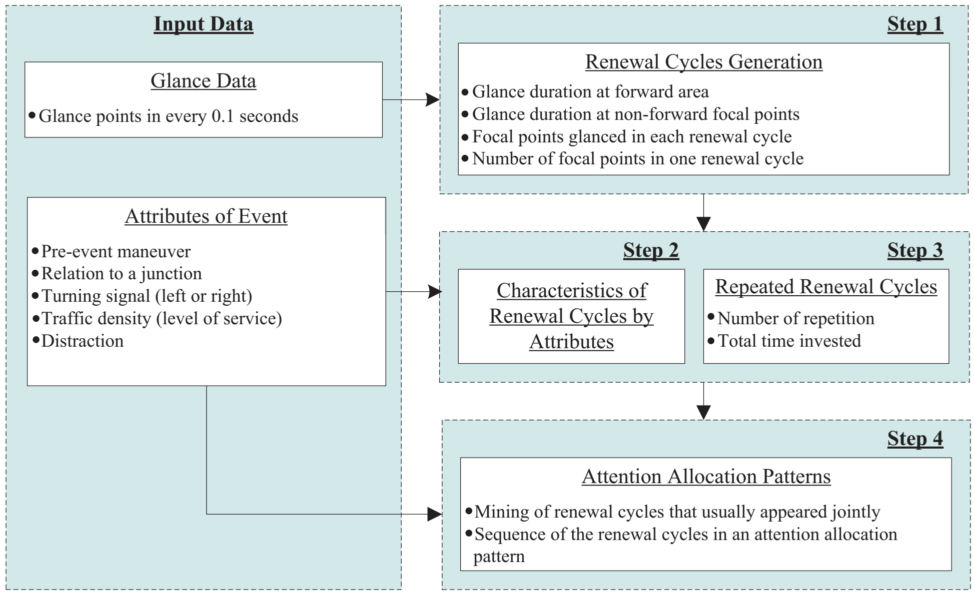

Fig. 1. Research framework for attention-allocation analysis.

The technique of *sequential association rule mining* has long been effectively applied to examine factors contributing to crash occurrence (Geurts et al., 2005; Pande and Abdel-Aty, 2009; Montella, 2011; Montella et al., 2012). Thus, this study adopted this method to mine the patterns of attention allocation composed of sets of jointly occurring renewal cycles. Based on the a priori principle, the sequential association rule mining method generates patterns (rules) by repeatedly adding new renewal cycles to existing patterns. The model's performance is evaluated after each addition, and patterns showing poor performance are pruned. A detailed description of the method can be found in, *Introduction to Data Mining*, by Tan et al. (2006).

3. Data

This study used the 100-car naturalistic glance data collected by the Virginia Tech Transportation Institute (VTTI) (Neale et al., 2002; Dingus et al., 2006; Klauer et al., 2006). The released online data included a baseline database and an event database. The baseline database contained only 6 s of glance data in each record, which is insufficient for this analysis. Therefore, this study adopted the event database, which contains 68 crashes and 760 near-crash incidents (VTTI, 2012).

The 100-car event database recorded drivers' visual glances and related attributes for the 30 s before crash or near-crash incidents. The 30-s duration was divided into two parts according to the precipitating events that were determined as causing the crash or near-crash incidents. Data collected after the precipitating events were related to emergency evasion and crash prevention. Such actions do not represent typical driver behavior. By contrast, data collected before precipitating events could be assumed to contain the time period that drivers were driving without being consciously affected by dangers and should be similar to the sample drivers' habitual behavior. Therefore, the data before the precipitating event (on average 25 s) were applied for the analyses. The drivers in the 100-car event database ultimately experienced crashes or near-crashes. The results derived in this study only represent the common patterns of a limited sample of drivers' behavior, which might include potentially risky behaviors.

Table 1 shows the attributes of the 100-car event database used in this study. Three types of attributes were used: roadway and traffic, driving tasks, and eye-glance data. The roadway and traffic-related attributes described the external conditions that drivers encountered. The driving tasks included the drivers' distractions, maneuvers, and turning signals.

The drivers' glance locations, including *Forward* (*F*), *Left Forward* (*LF*), *Right Forward* (*RF*), *Left Window* (*LW*), *Left Mirror* (*LM*), *Right Window* (*RW*), *Right Mirror* (*RM*), *Rear-view Mirror* (*ReM*), and *In-vehicle Distractions* (*InvD*), were recorded every 0.1 s. The period of continual glances to the same focal point is considered the glance duration. Among these focal points, InvD refers to all glances inside the vehicles, including the center stack, interior objects, cell phone, passengers, and instrument cluster. Each focal point received varying degrees of attention from different drivers.

Table 1
Attributes of 100-car event database.

Attributes	Category
Roadway and traffic	
Relation to junction	Non-junction, Intersections (Intersection, Intersection-related, Driveway, alley access), Other (Entrance/exit ramp, Rail grade crossing, Interchange Area, Parking lot)
Traffic density	Level of service (LOS) A to F
Driving tasks	
Pre-event maneuver	Driving straight (Going straight in constant speed, accelerating, but with unintentional "drifting" within lane or across lanes, Decelerating in traffic lane, Starting in traffic lane or Stopped in traffic lane), Lane Change (Passing or overtaking another vehicle, Changing lanes or Merging), Turning left and Turning right
Distraction (time series data)	Cognitive, cell phone, in-vehicle devices, external clutter, activity
Turning signal (time series data)	Recorded when turning signal (left, right and both) were on.
Eye-glance data	
Focal point (time series data)	Forward, Left forward, Right forward, Rearview mirror, Left window, Left mirror, Right window, Right mirror, In-vehicle distractions (Instrument Clutter, Center stack, Interior Object, Passenger, Cell Phone)
Duration of glancing at forward and other focal points	Continuous variable

To simplify the analysis, this study first analyzed only the areas where drivers glance, i.e., the InvD. Detailed characteristic differences among multiple locations or objects inside the vehicles were not considered.

This study excluded the first and final glances of each event in the glance data because we could not be sure whether they were complete glances. Any events with a glanced area recorded as “eyes closed” or “no video” were also excluded.

4. Results

4.1. Generated renewal cycles

In total, 2256 renewal cycles with 91 types were generated. The shortest renewal cycles contained only two glances: one forward and one non-forward focal point. The longest cycle contained 12 glances.

As shown in Table 2, the most frequent renewal cycles were 2-glance cycles, with 90.74% of the data falling into this category. A markedly smaller number of cycles were 3-glance, at 7.18%; and 4-glance cycles accounted for only 1.24%. Renewal cycles with 5 or more glances accounted for 0.85% of the data. This finding suggests that, rather than looking sequentially at various focal points within a single renewal cycle, the sample drivers usually separated their lapses from the forward direction into several sequences, directing their vision back to the forward direction after each visual shift.

The mean glance duration revealed that the sample drivers spend 3–4 s glancing forward and 1 s looking elsewhere. An increased number of non-forward glances per renewal cycle resulted in a longer cycle duration but a concomitant decrease in time spent looking forward, i.e., decreased mean, maximum, and standard deviation for forward-glance. The mean duration of each glance at non-forward focal points did not vary substantially across renewal cycles with varying number of glance points. However, the total time that drivers spent glancing off-road dramatically increased from 0.96 s in 2-glance renewal cycles to 3.00 s in 4-glance renewal cycles. This result indicates that a higher proportion of attention spent on multiple non-forward focal points in a renewal cycle was not compensated for by shorter cycle duration.

Nevertheless, there is a decrease in maximum and standard deviation of duration on both forward and non-forward focal points in 3- and 4-glance renewal cycles. This suggests that these drivers tried to avoid abnormal renewal cycles that involved dangerously long glances. The findings might illustrate the driver’s uneasiness when additional focal points were glanced at in a renewal cycle. The drivers who showed more glances in a renewal cycle were certainly less aware of the frontal area and incurred a higher risk of an accident. Thus, the 2.09% renewal cycles that showed more than three glances might have striking implications for accident prevention. This area of study deserves further attention.

4.2. Characteristics of renewal cycles by attributes

Table 3 shows the distribution of the common renewal cycles under various attributes. There were ten types of renewal cycles with more than a 1% frequency share, whereas eight types of 2-glance renewal cycles accounted for 90.74% of the frequency. Among the 2-glance renewal cycles, those involving in-vehicle distractions and rear-view mirror glances accounted for almost half of the generated renewal cycles.

To analyze the characteristic differences among various attributes, the distribution of these common renewal cycles under different conditions was examined. The recorded maneuvers and their relation to a junction were referred to the final pronounced action and associated location before a precipitating event. Such attributes did not necessarily exist throughout the entire 30-s data period. Certainly, the generated renewal cycles might occur before or during the maneuvering. Thus, it seems that a mismatch of time exists between eye-glance data and certain driving circumstances. Nevertheless, before implementing maneuvering intentions, drivers tend to look in the directions of future vehicle trajectories. That is, the entire maneuver includes searching for information, decision-making, and the final action. Analyzing only the exact period of the maneuver does not represent the entire attention allocation process. Thus, from this view point, the mismatch problem is ignored.

The attributes of a relation to a junction and maneuver were important for determining a driver’s expectations of potential threats. In these cases, a relation to a junction, road segments and intersections were the two main elements in the driving environment. When the drivers encountered intersections within 30 s, more renewal cycles of *RF* and *RW* would occur, probably because of the associated possibility of increased conflicts from the intersected roadway. Simultaneously, they allocated less attention to the rear side through the *LM*, *RM*, and *ReM*.

Lane changing and turning were the two primary maneuvers that naturally directed the drivers’ attention to directions critical for preventing conflicts. Meanwhile, drivers decreased the attention invested in non-safety related areas, such as *InvD*. The percentage of the renewal cycles in which the drivers transited attention to *InvD* decreased from 26.4% when driving straight to 12.4% when changing lanes, and to 17.4% when turning left or right. While changing lanes, the sample drivers increased their attention to the *ReM* and *LM* to observe the traffic conditions behind them.

In particular, the drivers transited their vision more frequently to the left side (*LW* and *LM*) when changing to the left lane, and to the right side (*RF* and *RW*) when changing to the right lane. The main difference between changing to left or right lanes was the use of the side mirrors. The *RM* was seldom used when changing to the right lane. One reason might be the faster driving speed in the inner (left) lane. Vehicles located in the right rear area were usually traveling relatively slowly. Once the drivers had successfully passed those vehicles, they had good information for where the vehicle was and could easily begin changing lanes to the right side without glancing at the *RM*. By contrast, vehicles in the left lane usually traveled more rapidly and required drivers’ close attention to ensure a safe margin for changing lanes to the left.

Turning at intersections was indicated to have an increased risk of crashing with traffic from an intersecting roadway in front of the subject vehicles. An increased number of renewal cycles involving *LF*, *RF*, and *LW* glances were found. For maneuvering a left turn, the *LW*, *LF*, and *RF* were the most common focal points for checking the potential threats coming from opposite traffic. Glancing at those focal points implied that threats were expected from the traffic passing through intersections. Another unique characteristic of turning left was the high percentage of the path from *Forward to InvD* (*F-InvD*). Turning was usually associated with complex tasks and few chances of shifting one’s attention to *InvD*. However, the drivers were more likely to stop and wait at the intersection when turning left than when turning right and changing lanes. In the absence of immediate crash risks, drivers may be inclined to use in-vehicle devices or interact with passengers while waiting. For a right turn, more potential conflicts were related to the traffic from the intersected roadway, pedestrians on the crosswalk, and cars following behind. Thus, the sample drivers paid greater attention to monitoring the *ReM*, *LW*, and *RW*.

Traffic density determined interactions with other vehicles. When traffic density increases from Level of Service (LOS) A to D, the sample drivers allocated more attention to the rear-view and left mirrors, probably checking traffic from behind or for lane changing. Moreover, the necessity for frequent speed adjustments and the

Table 2
Number of glances in renewal cycles.

	Number of glances				
	2	3	4	5 or more	Total
Frequency (%)	2047 (90.74%)	162 (7.18%)	28 (1.24%)	13 (0.85%)	2256 (100%)
Duration of forward glance (s)					
Mean	4.01	3.52	3.04	3.16	3.95
Standard deviation	4.91	5.04	4.19	3.15	4.89
Maximum	29.2	23.4	17.7	11.6	29.2
Duration of each non-forward glance (s)					
Mean	0.96	0.96	1.00	0.98	0.96
Standard deviation	0.93	0.71	0.48	0.70	0.91
Maximum	10.50	5.20	2.40	2.50	10.50
Mean duration of a renewal cycle (s)	4.96	5.43	6.04	8.25	5.05

shorter available reaction time associated with heavy traffic discourages drivers from engaging in non-driving-related tasks, such as transiting their vision from the forward areas to the roadside areas (*LW*, *RW*, and *RF*) or attending to *InvD*. When traffic density increased to LOS E, the sample drivers were unable to operate their vehicles freely but were forced to remain in the traffic stream. Under such conditions, drivers had ample opportunities to use in-vehicle devices because of the slow traveling speed and limited gaps available to merge with other vehicles. Thus, the percentage of *InvD* climbed sharply from 19.0% under LOS D to 29.9% under LOS E.

Among the common cycles, *InvD* were the main focal points on which the drivers spent a large portion of their non-forward attention time. As shown in Table 3, when distractions were present, *F-InvD* contributed 45.3% of the extracted renewal cycles. However, in the absence of distracting activities, 16.8% of the renewal cycles were still related to *F-InvD*. These findings suggest that engaging in distracting activity was not the only reason that the drivers transitioned their vision to in-vehicle focal points. At times, drivers transited vision inside their vehicles, despite doing nothing with in-vehicle devices. Because the sample drivers represented by this data set eventually experienced crashes or near crashes, it is reasonable to presume that defective behavior might have occurred in their daily driving operations.

4.3. Repeated renewal cycles

Occurrence of repeated renewal cycles could be considered an intention to complete a single task of obtaining information from specific focal points, continually checking the area of interest, or reconfirming traffic situations before maneuvers. Thus, the times of repetition and total duration provide meaningful measures that represent the different approaches of drivers in allocating their attention. Table 4 shows the duration of each non-forward glance in commonly found 2-glance renewal cycles, for both individual and repeated renewal cycles.

The focal point showing the highest percentage of repeated renewal cycles was *InvD*, of which 79.15% occurred repeatedly. Among the repeated samples, on average, drivers repeated the renewal cycles 3.58 times. For the total duration of glancing at *InvD*, the sample drivers spent 2.68 s on average. Because *InvD* represented all glances inside the vehicle, the repeated renewal cycle may contain different types of distractions. Consequently, accurate interpretation could be difficult. Fortunately, only 94 out of 429 repeated renewal cycles of *InvD* mixed with other types of distraction. These findings suggest that *InvD* tend to be rule- and knowledge-based activities that consume substantial attention resources to complete certain non-driving related activities, such as making a phone call.

Table 3
Distribution of renewal cycles by attributes.

Attributes	Sample size	Distribution of renewal cycles (%)										
		F-InvD	F-ReM	F-LW	F-LM	F-RF	F-RW	F-LF	F-RM	F-LM-LW	F-RF-RW	Others
Pre-event maneuver												
Driving straight	1827	26.4	22.3	13.5	9.6	8.1	6.2	3.9	1.4	1.0	0.8	6.8
Changing lanes	306	12.4	29.1	10.5	16.3	7.2	6.5	2.9	2.0	2.6	2.6	7.8
Turning left or right	116	17.2	19.8	22.4	0.9	16.4	2.0	6.0	0.9	0.0	0.9	10.3
Others	7	28.6	42.9	0.0	0.0	14.3	0.0	14.3	0.0	0.0	0.0	0.0
Turning signal												
Changing to left lane	44	2.3	20.5	15.9	38.6	2.3	0.0	6.8	0.0	9.1	0.0	4.5
Changing to right lane	43	7.0	23.3	4.7	7.0	9.3	18.6	0.0	4.7	4.7	7.0	14.0
Turning left	24	25.0	4.2	25.0	0.0	12.5	4.2	16.7	0.0	0.0	0.0	12.5
Turning right	21	0.0	23.8	23.8	0.0	19.0	9.5	4.8	0.0	0.0	0.0	19.0
Relation to a junction												
Road segment	1336	26.5	25.1	12.7	10.5	6.2	5.6	3.7	1.6	1.3	0.8	5.9
Intersection	582	24.2	20.1	13.9	6.5	12.5	7.2	4.0	1.2	0.3	1.5	8.4
Others	338	13.9	20.4	15.7	14.5	10.1	6.8	5.0	1.5	1.8	0.9	9.5
Traffic density												
Level of service: A	599	27.7	19.5	16.5	5.3	8.8	6.7	4.0	0.8	0.8	0.8	8.8
Level of service: B	822	22.7	22.3	14.8	8.9	9.7	6.1	4.0	1.1	1.5	1.6	7.3
Level of service: C	536	23.3	25.9	10.8	14.0	8.0	6.7	3.2	2.2	0.7	0.2	4.9
Level of service: D	232	19.0	26.3	9.1	16.4	5.2	5.6	6.0	2.6	1.3	1.7	6.9
Level of service: E	67	29.9	32.8	6.0	13.4	3.0	1.5	1.5	1.5	3.0	0.0	7.5
Level of service: F	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distraction												
Driving with distraction	572	45.3	16.1	9.1	6.6	5.9	4.4	1.6	1.2	1.4	0.3	7.0
Driving without distraction	1684	16.8	22.5	15.0	11.2	9.3	6.8	4.4	1.5	1.1	1.2	7.1
Total	2256	24.0	23.1	13.5	10.1	8.4	6.2	4.0	1.5	1.2	1.0	7.1

Table 4
Glance duration for non-forward focal points.

Focal point	Duration and frequency of each glance				Times of repetition[a]	Average total duration (s)[b]
	Individual renewal cycle		Repeated renewal cycle			
	Frequency	Duration (s) mean/std.	Frequency (%)	Duration(s) mean/std.		
InvD	542	1.14/1.04	429(79.15%)	1.19/1.10	3.58	2.68
ReM	522	0.64/1.03	312(59.77%)	0.66/0.54	2.90	1.05
LM	227	0.85/1.02	134(59.03%)	0.86/0.64	2.91	1.37
RM	33	0.82/0.38	14(42.42%)	0.84/0.38	2.80	1.13
LW	304	1.00/0.50	156(51.31%)	0.96/1.04	2.59	1.50
RF	190	1.08/0.68	69(36.32%)	1.01/0.98	2.48	1.37
RW	140	1.10/1.00	50(35.71%)	1.12/0.88	2.27	1.39
LF	89	1.16/0.95	26(29.21%)	0.97/0.79	2.36	1.44

[a] The calculation of repeated times included only the repeated renewal cycles.
[b] Both individual and repeated renewal cycles are included.

InvD were followed by *ReM*, *LM*, and *RM* glances, which respectively showed 59.77%, 59.03%, and 42.42% of the renewal cycles being repeated, with each repeating approximately 2.8–2.9 times. These repeated renewal cycles relating to mirrors showed almost identical mean durations, but less variance when compared to the mean durations of the individual renewal cycles. These results suggest that drivers were aware of the risk of paying inadequate attention to the forward direction by repeatedly searching and reconfirming activities. However, the stable duration of glances implied a required minimum time for the drivers to transit their vision and process information. Consequently, when facing tasks that pose a high information load, drivers might be unable to decrease the duration of each glance by increasing their sampling rates.

The sample drivers also frequently repeated the renewal cycles for the *LW*, *RF*, *RW*, and *LF*, and spent approximately 1.4 s to complete the search activity. Among these four focal points, the *LW* and the *RF* field, representing the roadside areas, showed a larger standard deviation for glance duration in repeated renewal cycles than that for individual ones. This phenomenon might be associated with the drivers' reaction to the different targets along the roadside. They might glance at those areas longer and repeat more frequently if interesting objects on the roadside attract their attentions. In the absence of interesting objects, drivers tended to transit their vision to the roadside areas briefly.

The sample drivers glanced at the *RW* for shorter intervals and repeated less frequently than the glances to the *LW*. Differences between glances to these two windows were probably related to the location of the driver's seat. Drivers sit beside the *LW* and can easily and comfortably transit their attention to enjoy scenic views through this window. Thus, the *LW* focal point showed an increased number of repeated renewal cycles and longer glance durations when compared to that of the *RW*. Finally, unlike the *RF* view, the *LF* field could be largely covered by the driver's peripheral vision of forward glances. Consequently, the percentage of renewal cycles for the *LF* field was the lowest among all focal points and showed the least repetition.

In addition to gathering/confirming identical information, repeated renewal cycles might also represent the task of continued observation of an area for new circumstances. In such cases, the renewal cycles that occurred repeatedly might be unrelated and simply reflect a common manner of driving. The question is how to tell the unrelated ones from the related ones. The inter-glance intervals of the non-forward focal point in the repeated renewal cycles could be good for judgment. Results of the inter-glance intervals showed that a big portion of the repeated renewal cycles related to *InvD*, *RW*, *RM*, and *LM* had relatively short inter-glance intervals (3.2–3.5 s) and were more likely for collecting and reconfirming information from the same target. On the other hand, some of the repeated renewal cycles related to the *ReM* had relatively long inter-glance intervals (4.5 s), suggesting probably just a common manner of driving.

4.4. Attention allocation patterns

One might ask whether the generated renewal cycles were interrelated or not. To answer this question, the Sequential Association Rule Mining package in SAS Enterprise Miner 6.2 was used to mine the sequential association between renewal cycles and combine related cycles into patterns of attention allocation, where the minimum support in this study was set at 5% and the minimum confidence at 10%. As stated, drivers displayed different renewal cycles under various road conditions and with various driver intentions. Hence, driving straight on a segment, passing through an intersection, and changing lanes on a segment were separated to mine the respective sequential association rules. Other types of maneuvers were not included because of the small sample size. Table 5 shows the derived attention allocation rules of the sample drivers for the three maneuver intentions.

The renewal cycles that included the *ReM* occurred in almost all extracted patterns of attention allocation. This finding suggests that paying attention to the front and rear areas of the vehicle were the two most crucial components for observing the surrounding traffic and maintaining situational awareness. The sample drivers usually transited their vision to these two areas immediately before or after shifting their attention elsewhere.

Driving straight on a road segment is relatively simple and has a light information load. In addition to the mentioned crucial renewal cycles, the drivers traveling straight on a road segment displayed the pattern related to *InvD* and *LW* glances. These cycles containing non-driving related information and, when combined with the above-mentioned crucial cycles, formed the attention allocation pattern for driving straight on a road segment. Such an attention allocation pattern can be described as drivers comfortably focusing on the front and rear areas, but intermittently and casually directing their attention to distractions on the roadside or inside the vehicles. The drivers also displayed the cautious behavior of transiting their vision from the *LM* to the *ReM* to maintain their situational awareness of the rear area, probably to monitor the blind zone on the left side.

For the maneuver intention of passing through an intersection, the drivers experienced a relatively heavy task load because of possible threats arising from the intersecting traffic. Compared with driving straight on a road segment, fewer notable patterns of renewal cycles were evident because the drivers were more cautious and concentrated on a few critical focal points when passing through an intersection. Apart from concentrating on forward and backward areas, the renewal cycle pattern *F-RF* → *F-LW* showed

Table 5
Attention allocation patterns of various maneuver intentions.

Patterns of renewal cycles	Driving straight on a segment		Passing through an intersection		Changing lanes on segment	
	Support[a]	Confidence[a]	Support[a]	Confidence[a]	Support[a]	Confidence[a]
F-InvD → F-ReM	9.23	24.51	5.97	18.18	9.09	42.86
F-ReM → F-InvD	8.49	16.43	8.21	23.4	–	–
F-LW → F-ReM	5.54	18.75	–	–	–	–
F-ReM → F-LW	5.54	10.71	–	–	10.61	20.59
F-LM → F-ReM	6.64	29.51	–	–	9.09	27.27
F-ReM → F-LM	–	–	–	–	9.09	17.65
F-ReM → F-RF	–	–	–	–	6.06	11.7
F-RF → F-ReM	–	–	–	–	7.58	35.71
F-RF → F-LW	–	–	5.22	20.59	–	–
Number of crashes or near crashes	271		134		66	

–: no pattern found.
[a] The confidence and support values are expressed as percentages.

that the drivers did not transit their vision far from one side of the vehicle to the other side, i.e., renewal cycle *F-RF-LW*. An intermediate glance at the forward side was adopted. The sample drivers usually looked to *RF* field initially, where conflicts with right-turning traffic would occur. Afterward they turned their vision to the *LW* to check for possible traffic emerging from the intersected road.

When changing lanes, drivers may encounter threats from multiple directions and must expend heightened effort to prevent possible conflicts, particularly conflicts from the adjacent lanes. Under these intense circumstances, the sample drivers' *InvD* were minimized and attention to the rear and side areas was strengthened. This finding suggests that the *ReM* was used in an auxiliary manner to enhance the drivers' situational awareness of the rear area, and that the *LM* was used to monitor the blind zone. Compared with the intentions of driving straight on a segment and passing through an intersection, the drivers evidently considered changing lanes to be a more mentally demanding task. Thus, after a renewal cycle for *InvD*, a relatively high proportion (42.86%) of the drivers immediately transited their vision to the *ReM* to gain information of the rear area relevant to changing lanes.

5. Conclusion

This study proposes the concept of the renewal cycle to analyze the entire process of driver attention allocation to understand the manner in which vision is transited among various focal points. Analyses of renewal cycles enabled identification of the characteristics associated with each focal point and the attention patterns that occur most frequently. Although these sample drivers were not representative, the results were promising and many of our findings offer potential for practical application.

5.1. Using renewal cycles to explore attention allocation

Instead of treating all focal points individually, the renewal cycle concept allows examination of the chain process and interaction among forward and non-forward glances. More than 90% of the renewal cycles identified in this study contained only one glance away from the forward direction. A large proportion of these cycles occurred successively and repeatedly; that is, the drivers might separate a long glance at one focal point, particularly *InvD*, into several repeated short renewal cycles. This finding supports the hypothesis that shifting attention away from the forward area decreases the driver's awareness of the traffic ahead. Thus, the sample drivers generally avoided looking away from the forward area for lengthy durations.

The duration of repeated renewal cycles may indicate the investment of mental resources in an information source. Because drivers separate lengthy glances on a focal point into several shorter successive renewal cycles, the traditional methods for analyzing the duration of each glance may underestimate the total effort expended on certain focal points. Analyzing the total duration of glances over repeated renewal cycles provides vital insight into the manner in which drivers manage information perception and/or reconfirmation of traffic conditions. Another advantage of the renewal cycle approach over that of the scan path is that it provides a clearer understanding of the visual transitions among focal points. In the traditional scan path approach, the most significant path comprises visual transitions to or from the frontal area, the most dominant focal point. This method cannot thoroughly reflect all visual transits around the vehicle. By using renewal cycles as the basic component of attention allocation, two seemingly distinct scan paths can be combined in an attention allocation pattern that illustrates the chain processes of drivers glancing at sequential focal points.

As expected, maneuvers that entail different task loads create distinct patterns of attention allocation. Moreover, the drivers exhibited patterns of transiting vision to the roadside or to in-vehicle devices to gain non-driving related information less frequently when they were busy performing maneuvers with higher task loads. This finding suggests the existence of compensatory behavior to prevent crashes by allocating increased attention to where the risk is increased (Liu and Lee, 2005; Törnros and Bolling, 2006). Nevertheless, in some risky situations, such as driving under LOS D/E, *InvD* were found to occur most frequently among all non-forward focal points. Drivers who overestimated their ability to handle both distraction activities and driving tasks placed themselves at increased risk of having a crash, especially under poor driving conditions. Hence, managing distraction is clearly vital for improving driving safety. Detailed analysis of distracted behaviors and their implications for designing effective information systems warrant further research.

5.2. Policy implications

The drivers in the 100-car event database used in this study experienced crashes or near-crashes. This implies that these drivers might have performed inadequate driving behaviors. The results of sample drivers' attention allocation from a renewal cycle perspective involve certain implications for preventing crashes.

The content of information offered to drivers and the manner in which the information is used are extremely relevant to safety improvement. The negative effects of using in-vehicle devices, such as cell phones or navigators, have been widely discussed (Patten et al., 2004; Horrey et al., 2006; Mcevoy et al., 2007; Caird et al., 2008; Kass et al., 2010; Thompson et al., 2012). The longer a driver transits vision away from the roadway to gain extra information, the greater the danger of losing full awareness of the traffic situation ahead. To evaluate the effect of an information system, a threshold for information-processing, such as the rule of 2-s off-road glance proposed by Klauer et al. (2006), should be considered. In this study, a large portion of renewal cycles that contained more than one non-forward glance were evidently over the safety threshold. The information load and manner of obtaining information have clear implications for traffic safety. Remember that the right message is required to change drivers' behavior. The possible side effects of distracting a driver's attention must be considered when designing an intelligent safety information system. Safety performance of an information system should be analyzed based on the dimensions of minimizing repetition, total duration, and duration of each glance when drivers seek information.

Attention allocation was regarded as a critical indicator that distinguished experienced drivers from novices, and safe drivers from unsafe ones (Konstantopoulos et al., 2010). The key concern of information seeking is the manner in which drivers transit vision among various information sources. The drivers' vision transiting away from forward for more than two glances might indicate that they did not allocate their attention resources properly and efficiently. In this study, in addition to the 10 types of representative renewal cycles, we found an additional 81 types of irregular renewal cycles, which contributed to the remaining 10% of frequency. In other words, a substantial proportion of renewal cycles may be atypical. Although this study did not focus on the characteristics of atypical or irregular renewal cycles and did not distinguish experienced drivers from novices, future research should investigate the problem of long glances away from the forward area. Such prospective research could be fruitful for educating drivers, particularly novice drivers.

Finally, this study contributes to the knowledge of both essential and nonessential focal points in terms of safety. These findings can be a preliminary step for future research to evaluate the risk associated with drivers shifting attention away from forward areas, and to identify the safety threshold for attention distraction required to reduce traffic crashes. By monitoring drivers' eye movements and comparing the patterns with regular attention-allocation patterns of safe driving, abnormal behavior could potentially be detected. Safety information systems might be able to alert the driver to lapses in attention or perhaps provide automatic control at times to help prevent crashes.

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