Visual Entropy Metric Reveals Differences in Drivers' Eye Gaze Complexity across Variations in Age and Subsidiary Task Load

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Abstract

The purpose of this study was to evaluate the global complexity of drivers' eye movement behavior as a function of advanced adult age and variations in information processing resource demands. Global complexity was operationalized using an information theory metric commonly known as ***entropy***. Fourteen young (mean age=27) and 14 older (mean age=75) participants drove on a 2-lane rural highway while simultaneously performing a subsidiary loading task designed to increase cognitive demands drawing upon either verbal-memory resources or visual-spatial resources (within the context of Wickens' (1980) multiple resource model of attention). Compared to traditional distributional measures of eye movement behavior such as mean saccade amplitude and fixation dwell time, the entropy measure of global complexity was better able to distinguish between young and old drivers as well as between baseline driving and conditions of high visual-spatial task load. These results strongly suggest that global measures of eye movement behavior hold significant potential for increasing our understanding of the interacting effects of normal adult aging and task-induced cognitive demands within the context of real-world driving.

INTRODUCTION

Older drivers demonstrate increased crash rates on a per mile traveled basis (Cerrelli, 1989). This trend is even more pronounced at intersections (Owsley, et al., 1991). Numerous investigators have attributed this increased automobile crash rate to age-related changes in fundamental aspects of visual information processing efficiency and/or visual attentional capacity (Ball, et al., 1993; Korteling, 1994; Schieber, 2000).

Monitoring and tracking eye movement behavior has proven to be a productive approach for improving our understanding of driving performance (see Green (2002) for a review). For example, Recarte and Nunes (2000) demonstrated that the spatial distribution of eye movements exhibited during driving tend to become truncated during the performance of a subsidiary task that required visual-spatial resources but not when the loading task required only verbal resources. Yet, very little is known about how eye movement behavior of drivers changes as a function of increasing adult age – especially in a real-world driving context. Most of the work involving real-world performance is limited to reading highway signs and is not easily generalized to other aspects of driving behavior (Schieber, et al., 2004; Zwahlen & Schnell, 1998).

If it can be assumed that older persons have diminished driving capacity resulting from decreased efficiency of visual information processing mechanisms then it follows that patterns of ocular exploration of the visual environment might be expected to differ as a function of driver age. The purpose of the present study was to explore this possibility by quantifying and contrasting the global complexity of eye movement behavior exhibited by young and older participants while driving. In order to attribute the hypothesized age-related decrease in eye movement complexity to changes in visual information processing capacity, *per se*, data were collected under conditions in which operator load was experimentally manipulated using a subsidiary task that increased demands upon either verbal or visual-spatial attentional resources. It was predicted that global eye movement complexity would be diminished in older drivers and that this trend would be exacerbated in the visual-spatial subsidiary task condition due to age-related shortfalls in the availability of visual-spatial resources (within the context of Wickens' (1984) multiple resource theory).

Entropy: A Metric of System Complexity

The *theory of information* (Shannon, 1948) provides a conceptual framework for quantifying the complexity of any control system – including the human saccadic eye movement system. Borrowing from the field of thermodynamics, this complexity metric has been termed ***entropy***. The entropy of a system is directly proportional to the amount of information necessary to describe the behavior of that system. That is, the more information needed to specify the system (and the state-space it can occupy) – the more complex the system. The time varying system with the highest entropy is one in which all state-to-state transitions are equally probable (i.e., random) while the least complex (zero entropy) system is one that is completely static and exhibits no state-to-state transitions.

Tole, et al. (1983) demonstrated that increases in pilot workload were associated with reductions in the complexity of their gaze patterns across a simulated flight instrument console. Their measure of eye movement complexity was based upon a variant of the entropy metric. Building upon their preliminary success, the current investigation adopted an entropy-based approach to quantifying the complexity of driver's eye movement behavior.

In order to compute a measure of entropy for a time series of eye movements it is first necessary to specify a meaningful set of discrete states into which individual glances may be categorized. In the current investigation, the driver's visual world was specified in terms of **7 discrete states** in a manner consistent with several theoretical assumptions regarding visually guided behavior. First, the outside visual world was divided into near (less than 2 sec preview time) and far zones in a manner consistent with Donges' (1978) two visual process model of automobile steering (i.e., near-compensatory versus far-anticipatory processes). Next, each of these zones was further subdivided into one central and two peripheral (left vs. right) subzones in accordance with Leibowitz and Owens' (1977) ambient-focal model of visually guided driving behavior (ambient = peripheral, focal = central vision). This 2 (near-far) x 3 (left-central-right) quantization of the visual environment was augmented by the addition of a seventh zone; namely, the vehicle's instrument panel, yielding a 7 state classification of the driver's visual universe.

Having established the rationale for a 7 state-space representation of the driver's visual environment, the algorithm for computing the visual entropy metric of eye movement complexity is as follows: (1) Collect a 10 min+ epoch of eye movement data while driving, (2) Assign each fixation to one of the elements of this state-space, (3) Find every event (Y_{ij}) where the eye gaze location transitions from one state to another, (4) Compute the conditional probabilities ($Y_{ij}|X_i$) of observing each of the 42 possible state transition sequences (see example shown in Table 1), and, finally (5) Compute the 1st order Markov entropy [H(Y|X)] of the eye movement sequence by applying Eq. 1 to this state-transition conditional probability matrix (see van der Lubbe (1997), page 86, Eq. 3.4).

Prior State				**Present State $p(Y_{ij}\|X_i)$**			
(X_i)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	------	0.166	0.166	0.166	0.166	0.166	0.166
2	0.166	------	0.166	0.166	0.166	0.166	0.166
3	0.166	0.166	------	0.166	0.166	0.166	0.166
4	0.166	0.166	0.166	------	0.166	0.166	0.166
5	0.166	0.166	0.166	0.166	------	0.166	0.166
6	0.166	0.166	0.166	0.166	0.166	------	0.166
7	0.166	0.166	0.166	0.166	0.166	0.166	------

Table 1. Sample matrix representing the conditional probability ($Y_{ij}|X_i$) of observing an eye movement transition from any given prior state to all possible destination states (N=42). This example represents the condition with the highest entropy (most complexity) since all transitions are equally probable. Applying Eq. 1 to this matrix yields H_{max} = 2.58 bits.

$$\mathbf{H(Y|X) = -\sum_{i=1}^{n}\sum_{j=1}^{m} p(Y_{ij}\,|X_i)\,\log_2\,p(Y_{ij}\,|X_i)\;p(X_i)}$$

Equation 1. Formula for computing the 1st order Markov entropy for an epoch of sequential eye movements assuming a 7 state model of the driver's visual environment. $p(Y_{ij}|X_i)$ refers to the conditional probability of a given state transition while p(Xi) refers to the overall probability of a transition originating from a given state.

An important property of the entropy approach to specifying the complexity of system's behavior is that the maximum possible complexity can be readily defined. Shannon (1948) showed that maximum entropy occurs when all system states (or, all state transitions in the case of a Markov process) are equally likely. For the current investigation, it can be shown that the maximum entropy (H_{max}) is 2.58 (See Table 1). This knowledge allows one to readily compute an index known as **relative entropy** wherein the entropy computed for an observed sequence of eye movements is normalized using division by H_{max}. This allows for a convenient interpretation; i.e., a relative entropy of 0.5 can be interpreted as a complexity level that is one-half of the maximum theoretical value that can be attained by the system being modeled. All subsequent references to eye movement entropy in this report will refer to relative entropy computed in this fashion.

METHOD

Participants. A sample of 14 young (mean = 27, range 19-35) participants was recruited from undergraduate psychology courses. Fourteen older participants (mean = 75, range 67-86) were recruited from community service organizations. Equal proportions of males and females comprised each age group. All participants held valid driver's licenses and had good visual acuity and hearing levels.

Apparatus and materials. All driving data were collected using a fully instrumented research vehicle (1998 Toyota Avalon with automatic transmission) equipped with an in-dash remote eye tracker (ASL model ETS-PC). In addition to collecting 60-Hz real-time eye gaze position and pupil diameter data, performance measures including speed, relative lane position, heading and steering wheel position were also logged at the same data rate. Subsidiary task stimuli consisting of brief digitized sound "clips" were delivered under computer control over a headset equipped with a microphone for recording vocal responses. Vocal responses were time stamped and recorded on the audio track of the eye tracker's scene camera video logger.

Procedure. Following administration of the university approved informed consent procedure, the visual acuity and hearing thresholds of all participants were measured. Drivers with poor vision or significant hearing loss were eliminated from the pool of participants. Each participant was then taken to the research vehicle and completed a "warm up" drive to become acquainted with its handling characteristics. While the vehicle was stationary in a parking lot, each participant experienced a series of 30+ practice trials with the subsidiary loading task stimuli which were presented in auditory form via the headset described above. The VERBAL subsidiary loading task stimuli consisted of a quasi-random string of numerical digits that were presented with a mean inter-stimulus interval (ISI) of 4 sec.

The participant's task was to answer "yes" if the stimulus was the same as the previously presented stimulus and "no' otherwise (i.e., a 1-Back Memory Task). The VISUAL-SPATIAL subsidiary load task stimuli consisted of a randomized sequence of time-of-day stimuli (e.g., "12:25" - pronounced "twelve, twenty-five"). Upon hearing an auditory presentation of a time-of-day stimulus, the participant was required to imagine that time as rendered on the "hands" of an analog clock. At this point, the participant was required to answer "yes" if either of the two angles formed by the hands of the imaginary clock was less than 90 degrees and "no" if otherwise (the so-called Clock Task). Thus, if the time-of-day stimulus was "12:25" the correct answer would be "no". The mean ISI between Clock Task stimuli was 8 sec. Prior work in our laboratory has established that performance of the Clock Task places significant demands upon spatial attentional resources (Schlorholtz, et al., 2006) .

Each participant completed 10 minute test drives under each of three experimental conditions: 1) no subsidiary load task (baseline condition), 2) while performing the verbal subsidiary load task, and 3) while performing the visual-spatial subsidiary load task. The order of the experimental conditions was randomized across participants. All driving took place on the same 2-lane (one lane each direction), north-bound, rural highway with a posted speed limit of 55 MPH. Drivers were required to obey the speed limit at all times.

RESULTS

Relative visual entropy metrics were computed for eye movement data collected under each of the experimental conditions and subjected to a (2) Age by (3) Subsidiary Load Task ANOVA. Because of instrumentation constraints, eye movement data were available from only 10 young and 6 older participants. Both the main effects of subsidiary load task ($F(2,24)=16.4$, $p < 0.001$) and the age by subsidiary load task interaction ($F(2,24)=9.8$, $p < 0.001$) yielded highly significant results. The nature of this interaction effect is graphically depicted in Figure 1. *Post hoc* analyses revealed a significant age group difference under the visual-spatial loading condition ($p < 0.03$). In addition, significant reductions in visual entropy (relative to baseline) were observed for the verbal task load condition among young drivers ($p < 0.003$) and the visual-spatial task load among the older drivers ($p < 0.002$).

Accuracy of subsidiary task performance was analyzed using a (2) Age by (2) Subsidiary Load Task ANOVA. Both the main effects of age ($F(1,22)=10.0$, $p < 0.004$) and load task ($F(1,22)=33.4$, $p < 0.001$) as well as their interaction ($F(1,22)=9.4$, $p < 0.006$) were significant. Although both groups exhibited reduced accuracy for the visual-spatial task, the significant interaction indicated this trend was slightly more pronounced for the younger (99 vs. 94%) as opposed to older (94 vs. 91%) drivers.

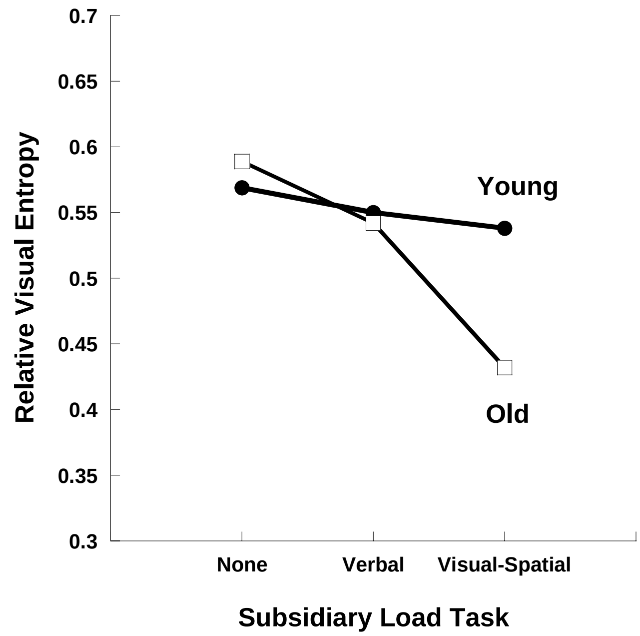

Figure 1. Relative visual entropy for 10-min epochs of eye movements as a function of driver age and concurrent subsidiary loading task activity.

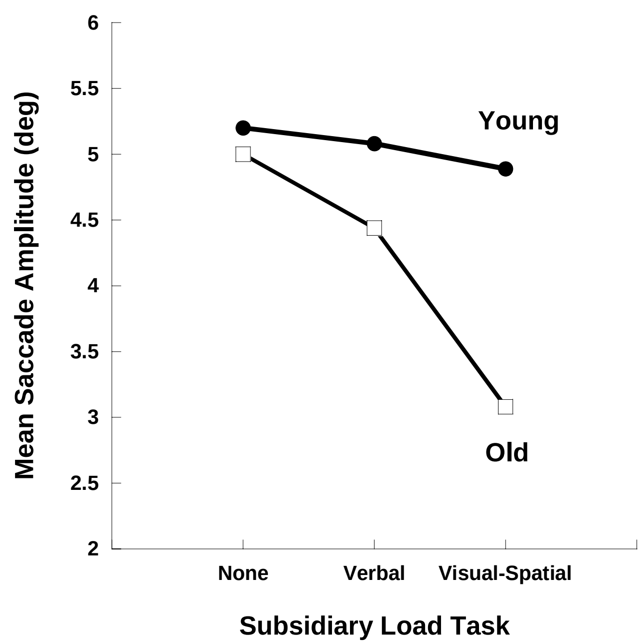

Figure 2. Mean saccade amplitude as a function of driver age and subsidiary loading task condition.

In addition to the analyses based upon the novel information theory metric of visual entropy, more traditional quantification of eye movement behavior using saccadic amplitude and fixation dwell time distributions were explored (see Figures 3 and 4). Mean saccade amplitude values were analyzed using a (2) Age by (3) Subsidiary Load Task ANOVA. Both the main effect of subsidiary load task ($F(2,24)=13.9$, $p < 0.001$) and the age by subsidiary

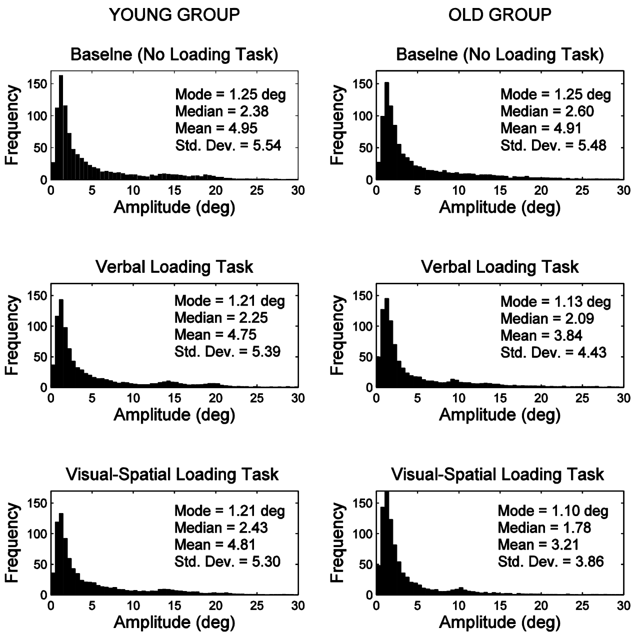

Figure 3. Saccade amplitude (degrees) distributions as a function of driver age and subsidiary loading task condition.

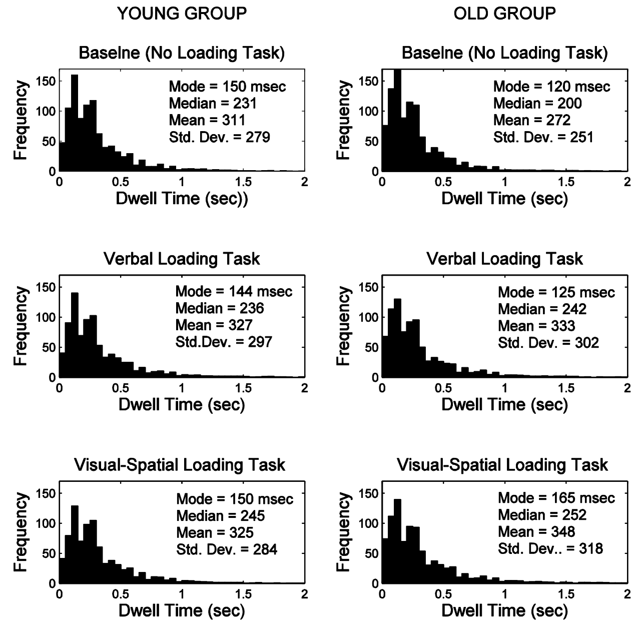

Figure 4. Fixation dwell time (msec) distributions as a function of driver age and subsidiary loading task condition.

load task interaction (F(2,24)=9.4, $p < 0.001$) yielded highly significant results. The nature of this interaction is graphgraphically represented in Figure 2. *Post hoc* analyses revealed no significant pair-wise effects of age for any of the subsidiary load task conditions; although the age effect observed for the visual-spatial load task yielded marginally significant results ($p < 0.06$). Among older drivers, significant reductions in mean saccade amplitude relative to baseline were observed for both the verbal ($p < 0.03$) and visual-spatial ($p < 0.003$) loading tasks. No such differences were observed among the young drivers.

Mean fixation dwell times were analyzed using a (2) Age by (3) Subsidiary Load Task ANOVA. Both the main effect of subsidiary load task (F(2,24)=8.4, $p < 0.003$) and the age by subsidiary load task interaction (F(2,24)=4.8, $p < 0.02$) were statistically significant. The nature of this interaction is graphically depicted in Figure 5. *Post hoc* analyses revealed a significant increase in fixation dwell time under the visual-spatial loading condition relative to baseline for the older drivers ($p < 0.01$). No such effect was observed for the young drivers.

Mean driving speed was analyzed using (2) Age by (3) Subsidiary Load Task ANOVA. Mean speed (53 MPH) did not change across loading tasks for young drivers but declined significantly for older drivers for both the verbal ($p < 0.02$) and visual-spatial ($p < 0.01$) loading tasks (47 > 45 > 43 MPH for the baseline, verbal and visual-spatial conditions, respectively. A similar pattern of results was observed for the speed variability data.

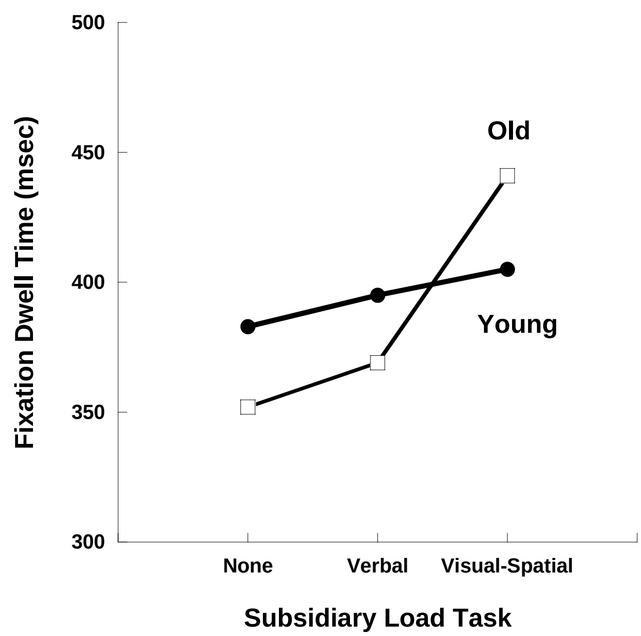

Figure 5. Mean fixation dwell time (msec) as a function of driver age and subsidiary loading task condition.

DISCUSSION

Application of the entropy metric has revealed that the global complexity of eye scanning behavior in a sample of young and older adults does not differ when driving on a low-volume, low-demand rural highway. However, the addition of an externally manipulated increase in cognitive demand using a subsidiary load task caused the complexity of ocular behavior to diverge as a function of driver age. Young drivers demonstrated a small (5.4%) but significant decrease in eye movement complexity under the demands of the visual-spatial load task. However, the size of this reduction in eye movement complexity was significantly greater (25.8%) for the sample of older drivers. No comparable effects were observed under the verbal memory task loading condition.

This pattern of results is consistent with previous claims that older drivers can be characterized as suffering from a shortfall in visual-spatial processing resources (as opposed to a more general processing deficit). This interpretation is supported by the observation that mean driving speed slowed significantly for the older (but not the younger) participants during the visual-spatial load condition. However, the ability of the current study to conclusively diagnose that the observed age difference represents a visual-spatial resource problem is limited by the fact that the verbal loading task was clearly less difficult than the visual-spatial task. The increased difficulty of the “clock task” was evidenced by the significant reduction in performance accuracy exhibited by both age groups. Future research will need to vary and/or equate task difficulty levels across verbal and spatial resource pools in order to make a definitive diagnosis of a domain-specific visual-spatial processing deficit while driving.

The comparison of the global complexity findings to more traditional measures of eye movements was instructive. The entropy measure was able to discriminate the effects of increased subsidiary task workload upon ocular behavior among both the young and old drivers. Once more, the entropy metric was able to reliably differentiate the behavior of young versus older drivers under the high visual-spatial load condition. The mean *saccade amplitude* parameter exhibited none of these discriminative properties and excelled only with respect to discriminating between the verbal and visual-spatial load conditions. Yet, even this benefit was constrained to comparisons within the old group. The mean *fixation dwell time* data revealed that older drivers exhibited fewer and longer glances under the visual-spatial load condition. This information complements the entropy findings rather than compete with them.

In summary, the current study has garnered evidence that global measures of eye movement complexity vary systematically with increasing driver age; and, manipulations of driver information processing demands. These findings suggest that future efforts to apply global metrics based upon information theory hold significant potential for increasing our understanding of driving-related behavior.

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Acknowledgements

Special thanks to *Toyota USA* for providing the instrumented research vehicle to the lab. The ASL ETS-PC eye tracker was purchased through the generous support of the National Science Foundation.