BEHAVIORAL ENTROPY AS A MEASURE OF DRIVING PERFORMANCE

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Summary: Delayed event detection and degraded vehicle control are observed when drivers fuel their need to perform extra-driving activities. Vehicle control and event detection are shown to degrade most if the in-vehicle task requires spatial cognitive resources and/or if the activity requires visual perception and/or manual control manipulation. In-vehicle tasks with auditory input and/or voice output that primarily demand low levels of verbal cognitive resources appear to affect event detection only to a small degree and seem to have no effect on vehicle control. A theory-based approach to measure, analyze, and interpret these performance assessments. Results from our SAE paper #1999-01-0892 are used as a vehicle to demonstrate that steering entropy (a measure of vehicle control) in conjunction with reaction times to unpredictable peripheral events (a surrogate measure for event detection) offer clear insight into the safety consequences of various in-vehicle tasks. These results are here discussed in the context of a simple linear predictive model that is based on Wickens' theory of multiple resources. The model is shown to offer useful predictions about and interpretations of the effects that various in-vehicle tasks have on driving performance in general and driver distraction in particular.

INTRODUCTION

Key to enriching our understanding of human drivers is to understand how they view performance. Drivers interject corrective control actions when the driving situation reaches an unacceptable state. Acceptability is the decision threshold that bounds the safety-zone within which drivers prefer to operate. This decision threshold is modeled as the outcome of a satisficing decision maker who seeks domains of operation that are more beneficial than costly. By categorizing drivers' needs in terms of motivational (beneficial) and constraining (costly) components, we can employ formal tools to explain within- and between-driver variability and obtain a method to quantify performance (Boer et al., 1998). The key to monitoring driver performance is not to measure variability but to quantify the corrective actions that signal drivers' dissatisfaction with the current driving state. By defining workload as the effort required to maintain the driving state within the subjective safety zone, subjective performance and (subjective) workload become anti-correlates. Subjective performance is a complex construct that can be linked to the degree of understanding about the situation or the degree to which the operator feels in control of the situation. The signature of a lack of understanding and a lack of control is an erratic, unpredictable, and inefficient behavior that we quantify with an entropy measure (Boer, 2000). These signatures are also observed in eye-movements, in interaction with interfaces, and in control of dynamical systems.

Corrective actions are often the result of prolonged attention diversions or other interferences caused by extra-driving activities such as changing a CD or eating. A measurement technique that captures these corrective responses offers a means to quantify how distracted (inattentive) a driver is and a

means to operationally determine the driver's safety margins. Steering entropy as described by Nakayama et al. (1999) and Boer (2000) is such a measure; it quantifies the steering profile's predictability. As drivers adapt their behaviorally acceptable region, either because of shifting needs or because of a realization that they cannot maintain their own safety standard, they effectively control the number of necessary corrective responses. This results in a less predictable steering profile or equivalently in a profile with a higher entropy (i.e. higher information content).

EXPERIMENTAL DESIGN

The data described in Nakayama et al. (1999) was collected in a real-cab driving simulator with realistic steering and pedal feel. The driver's task was to follow a speed modulating lead vehicle, along the winding country road. Four participants performed four sessions each over a period of two days. Each session consisted of 9 trials of 3min each. During each session they either performed no additional in-vehicle tasks (1st and 9th trial in each session) or performed a specific in-vehicle task as frequently as comfortably possible. In two of the four sessions a peripheral detection task (PDT) was performed in conjunction with performing the in-vehicle tasks. The PDT setup consisted of three LEDs positioned on the dashboard, one of which illuminated on average, once every 10-30s. The subjects were instructed to press a thumb-activated button on the steering wheel quickly as possible when one of the LED illuminated. In the other two sessions they did not perform the PDT, but sill performed the in-vehicle tasks. Each symbol in Fig. 1 (left panel) denotes the average steering entropy against the average reaction time for a particular in-vehicle task. The numeric labels in the figure correspond with those in the table. Averages were taken over all subjects.

MULTIPLE RESOURCE THEORY: IN-VEHICLE TASK ENCODING

The 14 tasks used in the Nakayama et al. experiment are encoded below in terms of estimated interferences based on Wickens' theory of multiple resources (2000). He distinguishes between: processing stages (perceptual/cognitive versus response selection/execution), perceptual modalities (auditory versus visual), and processing codes (verbal versus spatial). Driving is a multi-task that demands visual-spatial resources from both processing stages. The theory predicts extra-driving tasks that require auditory/verbal resources will interfere less with the driving task than those that compete with the visual-spatial resources demanded by the driving task itself. The 14 in-vehicle tasks used in the Nakayama et al. study are briefly described in Table 1. The shaded columns in the table are used as input variables to the model presented below. They represent the relative degree to which each task taps into the various resource components.

The purpose of this paper is not to produce a set of generally applicable encoding rules but to show that a simple linear model operating on a reasonable task encoding has high predictive value in terms of the effect that a wide range of in-vehicle tasks have on vehicle control and event detection. Tasks are encoded according to the following rules. The way in which the task presents information to the driver (i.e. auditory driver input I_A and/or visual driver input I_V in columns 5 and 6 respectively) is simply encoded with a 1 if that modality (auditory or visual) is used by the task and a 0 otherwise. The same encoding strategy is used for the way in which the driver presents information to the task (i.e. voice driver output O_V and/or manual driver output O_M in columns 13 and 14 respectively). Encoding of the cognitive resources is separated into two processing codes: those related to verbal resources (i.e. C_V which is modeled as a linear combination of working memory WM_V in column 8 and cognitive processing CP_V in column 9) and those related to spatial resources (i.e. C_S, the linear combination of WM_S in column 11 and CP_S in column 12). The working memory (WM) load (columns 8 and 11) is encoded as the estimated number of verbal and/or spatial chunks (items) that

the driver has to keep track of simultaneously (e.g. task 4 has four items, 3 answers and a question). The cognitive processing load (columns 9 and 12) is encoded according to a scale ranging from 0 to 3 whereby a value of 3 corresponds to the most cognitively demanding task (i.e. tasks 4 and 5).

As indicated in the previous paragraph, working memory and cognitive processing are not directly used as input variables to the model (i.e. are not shaded in the table) but combined as follows:

$$C_V = \min\{3, \lceil (WM_V + CP_V)/2 \rceil\} \text{ and similarly } C_S = \min\{3, \lceil (WM_S + CP_S)/2 \rceil\} \qquad (Eqn. 1)$$

where $\lceil X \rceil$ is the ceiling operator (i.e. the smallest integer value greater than X). These two composite variables are shown in columns 7 and 10. The combination rule in Eqn. 1 is motivated by: (i) the fact that assigning values to working memory and cognitive processing load is rather ambiguous and (ii) the need to prevent the model from focusing too much on the idiosyncrasies of our experiment (i.e. model the noise rather than the underlying trends). The latter is a serious concern when the number of model coefficients begins to approach the number of observations.

A PREDICTIVE MODEL OF IN-VEHICLE TASK INTERFERENCE

The following linear models fit the steering entropy and reaction time data best (using Matlab function `lsqnonneg`):

$$1000SE_{mod} = 454.4 + 0.0I_A + 7.2I_V + 8.6C_V + 28.3C_S + 0.0O_V + 136.0O_M$$
$$RT_{mod} = 361.0 + 0.0I_A + 0.0I_V + 12.1C_V + 24.2C_S + 31.0O_V + 130.3O_M$$

$$(Eqn. 2)$$

Coefficients were constrained to non-negative values because any utilizations of the component resource pools is assumed to decrement performance. Even though a model that allows for negative coefficients results in a slightly better fit (Corr. Coeff. for steering entropy goes to 0.9543 from 0.9396 and for reaction time it goes to 0.8845 from 0.8828 using the Matlab function `robustfit`) the results become much more difficult to interpret and appreciate. The primary reason for this difficulty is that the model input variables (columns 5-14 in Table 1) are highly correlated as a result of the adopted set of tasks. This makes it difficult to interpret the meaning of the coefficients without explicitly taking the input correlations into account. To perform a proper analysis that can also determine the degree to which the various resources are independent, a set of tasks needs to be established whose encodings are orthogonal - a challenging exercise.
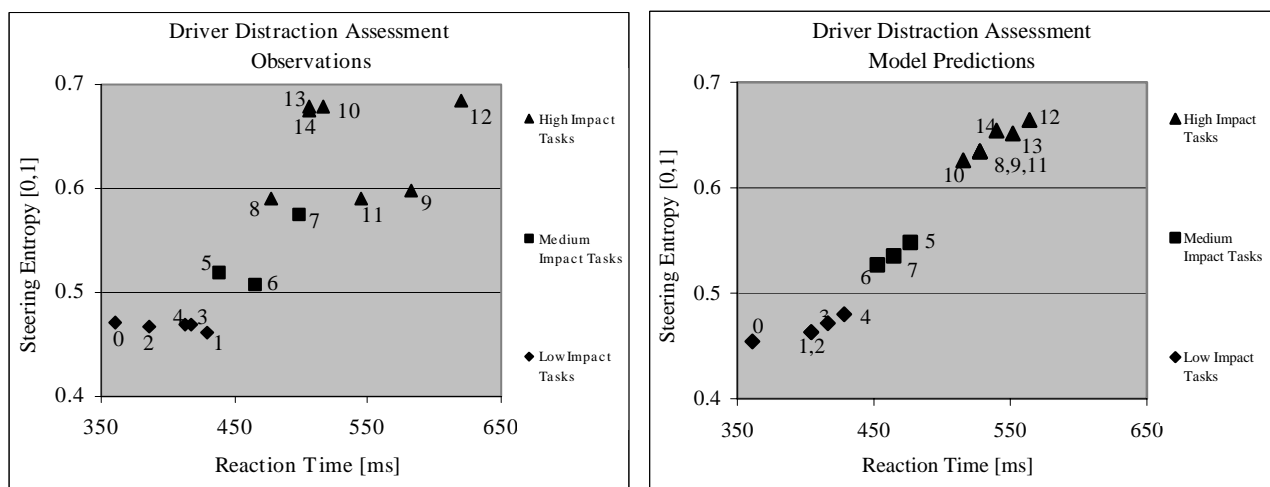

Figure 1. Observed (left panel) and model predicted (right panel) driving performance measures for the 14 different in-vehicle tasks described in Table 1. The x-axes show drivers' average reaction time in the peripheral detection task and the y-axes show drivers' steering entropy (see Nakayama et al, 1999 for details). The left panel shows observations and the right panel shows predictions from the model given in Eqn. 2. The three model motivated impact levels are also reflected in the shading of columns 1-4 in Table 1.

The well-known vigilance enhancing and therefore performance improving effect of low demand in-vehicle tasks (e.g. listening to the radio) is ignored here because it is not believed to play a significant role in our experiment. To model this vigilance effect, negative coefficients would be necessary. The observed slight drop in steering entropy for the "low impact tasks" may be due to vigilance (i.e. a slight increase in control accuracy that reduces the magnitude and frequency of encroachments to the boundary of the safety zone), but can also be attributed to, for example, an increase of the safety tolerance that has the same steering entropy reducing effect. Even though multiplicative and higher order dependencies of driving performance on resource distribution and utilization are also not captured by the model, the fact that the model correlates so well with the observations suggests that these terms are of secondary importance. This is consistent with the assumption that the various resources pools are largely independent (Wickens & Hollands, 2000).

Table 1. The in-vehicle tasks listed in column 2 are encoded in accordance to the theory of multiple resources (columns 5-14). Observed and model predicted driving performance measure for reaction time to a peripheral detection task and for steering entropy are shown in columns 3 and 4 respectively. The levels of shading in columns 1-4 reflects three levels of model predicted interference that are also indicated in the right panel of Fig. 1 by horizontal lines. The shaded columns (i.r. 5,6,7,10,13, and 14) are input variables to the steering entropy and reaction time models given Eqn. 2.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Task	Task Description	Results		Numeric task encoding according to the Theory of Multiple Resources									
		PDT RT	SE	Input	Input	Code	WM	Cog Proc	Code	WM	Cog Proc	Output	Output
				Auditory.	Visual.	Verbal	Verbal	Verbal	Spatial	Spatial	Spatial	Voice	Manual
		RT	$1000\,SE$	I_A	I_V	C_V	WM_V	CP_V	C_S	WM_S	CP_S	O_V	O_M
		Observation / Model	Observation / Model	Yes (1) / No (0)	Yes (1) / No (0)	Rating [1,3]	# Items	Scale [0,3]	Rating [0,3]	# Items	Scale [0,3]	Yes (1) / No (0)	Yes (1) / No (0)
0	Null – Driving Task	361 / 361	471 / 454	0	0	0	0	0	0	0	0	0	0
1	Listening for traffic information at specified location.	429 / 404	462 / 463	1	0	1	1	1	0	0	0	1	0
2	Repeat words spoken by experimenter.	386 / 404	468 / 463	1	0	1	1	1	0	0	0	1	0
3	Give yes/no answers to simple questions.	417 / 416	469 / 472	1	0	2	1	2	0	0	0	1	0
4	Select one of three given answers to a question.	413 / 428	469 / 480	1	0	3	4	3	0	0	0	1	0
5	Subtract 7 repeatedly starting at number around 950 [*]	439 / 477	520 / 548	0	0	1	1	1	3	2	3	1	0
6	Check map position and name of location shown on navigation screen.	465 / 453	508 / 527	0	1	1	1	1	2	1	2	1	0
7	Look at list of 4 names on display and select favorite.	498 / 465	575 / 535	0	1	2	2	2	2	2	1	1	0
8	Change AC mode as instructed by pushing switch next to screen.	477 / 528	591 / 634	1	1	1	1	1	1	1	1	0	1
9	Change AC mode as instructed by pushing touch screen button.	583 / 528	599 / 634	1	1	1	1	1	1	1	1	0	1
10	Scroll map according to the highlighted route.	517 / 516	679 / 626	0	1	0	0	0	1	1	1	0	1
11	Change map scale so that specified location is visible.	545 / 528	591 / 634	1	1	1	1	1	1	1	1	0	1
12	Take specified amount money from various coins in console box.	620 / 563	685 / 664	1	0	2	2	2	2	2	2	0	1
13	Pick up cellular phone and dial specified number.	506 / 552	679 / 652	1	1	3	7	2	1	1	1	0	1
14	When phone rings select it from the box with several similar sized items.	506 / 540	675 / 654	1	1	0	0	0	2	1	2	0	1
		Corr.Coef. 0.8828	Corr.Coef. 0.9396										

[*] It is assumed that subjects solve the arithmetic task primarily spatially (i.e. visualize the numbers) even though there are large individual differences in how people solve such tasks (some perform them 100% verbally whereas other adopt a 100% spatial strategy).

CONSEQUENCES FOR VEHICLE CONTROL AND EVENT DETECTION

The model shows that steering entropy is primarily affected by tasks that rely on spatial resources (i.e. visual input, spatial processing code, and manual output). On average, 90% of the increment in steering entropy is attributed to spatial resources and only 10% to verbal resources (i.e. auditory input, verbal processing code, and voice output). This was expected because vehicle control is a visual/spatial/manual task. Even though reaction time is also significantly impacted by tasks that tap into spatial resources, it is also strongly affected by verbal tasks. On average 26% of the increment in reaction time is attributed to interference from verbal resource and the remaining 74% to spatial resources. The majority (59%) of the vehicle control interference stems from the response selection/execution processing stage. The same holds for event detection , 65% of the increase in reaction time is attributed to interference from the response selection/execution stage. The fact that the response selection/execution component of an in-vehicle task interferes more with driving performance than the perceptual/cognitive components is consistent with, for example, Pashler's work on the existence of an attentional bottleneck in response planning (1998).

It is tempting to generalize this finding by stating that (i) vehicle control is primarily affected by tasks with a spatial component and that verbal task components have little impact on vehicle control, as well as that (ii) event detection is also most strongly affected by tasks with a spatial component but the impact of verbal task components is considerable. However, this generalization is premature and requires close scrutiny. The main phenomenological reason for degraded event detection when performing verbal tasks is attributed to the repeated finding that drivers' eyes and therefore perhaps spatial attention move around less as the cognitive demand of in-vehicle tasks increases (e.g. Recarte & Nunes, 2000). This partial cessation of eye movements may be due to the simple fact that no more information can be processed which makes eye movements non-productive. This hypothesis is consistent with existing limited resource theories.

CONCLUSION

It is motivated that a combination of a driver-centered vehicle control performance measure in the form of steering entropy, and an event detection performance measure in the form of reaction times, together with measures of adopted safety margins, offers the necessary approach to quantify the level of driver distraction incurred by a wide range of extra-driving activities. Sufficiency of the proposed approach can only be assessed when the causal chain from degraded performance to accident susceptibility has been established and the transfer from simulator or instrumented vehicle results to real world driving is fully understood.

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