EFFECTS OF CONTROL'S VERTICAL LOCATION, DESIGN, AND USE ON DRIVER'S VISUAL BEHAVIOUR

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ABSTRACT: The aim of this paper is to explore the diversity of psychological aspects affecting drivers' visual behaviours with dashboard controls. Two driving simulator experiments were conducted in order to study these aspects. In the first experiment, drivers' visual behaviours were analyzed while using different manual controls located near the gear stick compared to controls located near the windshield. The second experiment further studied these issues by investigating the moderating effects of speed and cognitive load which were also assumed to affect the visual behaviour of drivers. The results suggest that only a few of the factors that affect the visual behaviour of the driver in a dual-task situation with manual controls are related to the physiological aspects of the human operator. On the whole, the results demonstrate the active role of the driver in evaluating task demands and adapting one's behaviour accordingly in dual-task situations while driving.

1 INTRODUCTION

The amount of different in-vehicle systems (IVS) which require operations from the driver in modern vehicle dashboards is increasing. At the same time, the average age of the driver population is growing which places requirements to design IVS cognitively and visually low demanding. This phenomenon should be considered especially with novel ITS-related functions, as they may place more cognitive demands on the driver because of their multi-step nature and complexity compared to the more traditional in-vehicle user interfaces [1].

There are some general guidelines for display positioning in vehicles which suggest for example that the closer the display is to the windshield, the shorter is the glance time off road (e.g., [2]). This guideline can be supported by the physiological fact that the longer the distance between two points of focus, the longer the time required to shift and focus eyes between them. The purpose of this guideline is to minimize the glance times off road while glancing the displays. However, this design principle is not necessarily sufficient if applied to manual secondary controls. Based on the physiological features of the driver, human factors guidelines may suggest, for example, that the most frequently used controls should be located within fingertip reach or that the controls should be located near the driving scene to minimize the glance time off road when locating and using them (e.g., [2-4]).

Surprisingly, empirical research by [5] suggested that locating manual controls far from the driving scene may actually minimize the glance time off road. One explanation for this phenomenon could be that the driver's perception of risk is high when using controls at this location which encourages the driver to use the controls without visual attention. The goal of the experiments reported in this paper was to examine this explanation and the related issues raised by the experiments in [5]. The main purpose of the first experiment was to investigate if there is a difference in driver's visual behaviour while using secondary controls located near the gear stick compared to the pattern of behaviour with controls located near the windshield. It was hypothesized that drivers prefer to use the controls without visual attention if these controls are located so that peripheral vision can not be used to observe the driving scene during operating the controls with the visual focus on these (see [6, 7]). The explanation for this kind of adaptive visual behaviour was hypothesized to be the driver's experience of risk and evaluation of task demands (see [8, 9]) while executing a secondary task with the aid of visual attention and driving. Losing all visual information from the environment while using the controls was assumed to raise the level of experienced risk. A significant moderator in the learning process was suggested to be the possibilities for automation of motor skill through practice which is assumed to be affected by the control's shape coding. In the second experiment, the issues raised by the first experiment were further examined by studying two additional factors which were also assumed to affect the visual behaviours of drivers according to research literature. These factors were the cognitive demands of the secondary task (e.g., [10]) and the demands of the driving task (e.g., [11]).

2 EXPERIMENT 1

2.1 Experimental design

The first pilot experiment of explanatory nature included four trials per subject with 12 subjects. A between-subject design (High-Low) was used in order to reveal the effects of the vertical location of controls in relation to the subject and to control learning effects. The lower location was a position, where the subject could not use peripheral vision anymore to aid lane-keeping while fixating at the controls. Three different types of controls were used as a within-subject factor of control type: a row of black switches with one blue and one green switch (colour interface), a dial pad similar to mobile phones (dial interface) and a rotary switch with four positions (rotary interface).

2.1.1 Subjects

The 12 volunteer subjects, eight females and four males having a valid driver's license, were recruited via public email lists of the University of Jyväskylä. To control the effects of different distances from subjects' eye levels to the controls, the height of the recruited subjects was set between 162-180 cm (M=169.33 cm, SD=6.08 cm), The subjects' age varied between 20 and 26 years (M=23.4, SD=1.8). They were not informed about the purpose of the experiment and were rewarded with a movie ticket for the participation. The 12 subjects were divided into two groups of six which were balanced on the basis of driving experience, age, and gender. The two groups had different positions for the secondary controls. The subjects were ordered as similar pairs as possible between the groups according to the aforesaid factors to mitigate the possible effects of these factors in the results.

2.1.2 Tools and environment

Experiments were conducted in the Agora User Psychology Laboratory at the University of Jyväskylä with a fixed-base driving simulation. Lighting in the facility was dimmed to ensure good visibility of the projected driving scene. A freeware Racer driving simulation was modified for a more realistic driving experience. The track used in the experiment simulated a road on the Norwegian countryside with downhills, uphills, and tight curves. Solid white lane markers were drawn into the road. The car used was a Ford Focus with an automatic transmission. The information of vehicle speed was projected on the windshield with an analogue speedometer simulating head-up display data. The overall hardware used included: a data projector, a simulator computer, a steering wheel with force feedback and pedals, an adjustable dashboard with three types of secondary controls, a set of speakers, digital A/V-capturing devices, and a portable computer for gathering experimental data. Distances between the controls were: steering wheel centre—dashboard 33 cm, steering wheel centre—projected driving scene 105 cm, steering wheel centre—pedals 60 cm, floor—dashboard controls 75 cm for the High group and 55 cm for the Low group. The size of the projected driving scene was 110 cm x 75 cm. The effects of discrimination aspects and motor control differences were controlled in the design. The dashboard included three different types of controls (see Figure 1) which could be easily discriminated from each other without visual attention. There were no differentiating guidance cues between groups for movement while using the different controls and the pattern of movement for each control type was not similar with the use of a gear stick. The controls were located so that the movement pattern of hand was similar in the two groups and between the different control designs.

Fig.1. The dashboard controls

However, the controls differed from each other with their design. The rotary interface had four positions, made a clear clicking sound when rotated from a position to another, and the selected position was shown by a number at the top. The position of the rotary interface was also possible to remember and count from the number of clicks when rotated. The colour interface included a row of five similar two-position switches. Three switches were black and between them was a green and a blue switch which were the ones used in the tasks. The locations of the colour switches were possible to learn to remember and feel without the use of visual attention by remembering that they were next to the switches on the edges. However, this was difficult because the states of the switches altered (up-down) in use and it was demanding to feel where one switch ended and another began. The controls gave feedback by making a click when pressed. The third type of control was the dial interface. The buttons '8' and '0' were used in the experiment. The use of these buttons was also possible to learn without using visual attention by touching the two lowest rows on the dial pad. However, this was also quite demanding because the buttons were similar to each other and very small in size. Furthermore, the dial controls gave no auditory feedback. Synthesized speech was used to tell the secondary tasks with the colour interface. With the other controls the tasks were given by the experimenter with a monotonic and calm voice.

2.1.3 Procedure

After gathering subject's background information, the first trial was driven without the secondary tasks in order to get the subject familiar with the driving task. The following three trials were driven with the same route as the first one, but a total of 19 surrogate selection tasks with the secondary controls were completed as instructed while driving, one control type per trial. Before these trials the subject was instructed in the selection task and completed four rehearsal selection tasks with a secondary interface (rotary, colour, or dial). The rehearsal tasks were '2', '0', '3', '0' (rotary); 'blue', 'green', 'blue', 'green' (colour) and '0', '8', '0', '8' (dial). The subject was informed to drive the route through without time pressure and that the goal of the driving task was to keep the vehicle as accurately as possible on its own lane. They were advised to drive as they normally would in area of 80 km/h speed restriction, but to adjust their speed according to the situation. The subject was instructed to react in the selection task according to the instructions provided by the experimenter and to complete the task as soon as it seemed safe. This allowed the subjects some tactical freedom in deciding when to perform the selection task. Stopping the vehicle was not allowed during the selection tasks. The speed of the car should not either decelerate to a ridiculous level, considering the driving situation. The selection tasks and the driving task were instructed to have equal priority. The subjects were informed that the one who gets the lowest number of errors (lane excursions and selection task errors) gets another movie ticket. This informing was done to encourage the subjects to try their best in the tasks and to eliminate sensation-seeking and carelessness in the simulated driving task. The order of the control types and the order of the selection tasks were randomized. The selection tasks were given in predetermined points on the track. After each trial the subjects reported the experienced task demand, performance, frustration level, and experience of risks of driving task errors while completing secondary tasks to a modified NASA-Task Load Index (TLX) questionnaire [12].

2.1.4 Data analysis

After the trials, the subjects were asked to rate the perceived task load on a modified NASA-TLX form (no weighting) and to rate on a similar scale the perceived risk of driving task errors while using the secondary controls at the beginning of the trials and after practice. Glance times off road, speeds, and lane excursions were scored from the video material by using high quality software for behavioural research. Lane excursion was defined to occur when the vehicle's visible part, the blue bonnet, exceeded the lane markers. The wrong selections in the selection tasks were noted real-time during the trials. The number of glances and total glance time (TGT) off road were scored manually from the recorded video frame-by-frame. Non-parametric statistical tests, Wilcoxon Signed Rank Test and Mann-Whitney U-Test, were used to analyse the statistical significance of the differences between the groups and between the different control types.

2.2 Results and discussion

2.2.1 Lane excursions and selection task errors

There were no statistically significant differences in the number of lane excursions between the groups with any of the control types. However, four subjects drove off the road during the trial. Three of them were in the High group. Only 11 wrong selections were made in the selection tasks of the total of 684 tasks (colour: 7, rotary: 4).

2.2.2 Visual behaviour

Maximum length of a glance off road was 1.5 seconds while the minimum length of glance off road was 0.3 seconds. There were no significant differences in the visual behaviours between groups with any of the control types. However, the visual behaviours varied significantly between the rotary interface and the other control types (see Table 1). The mean number of glances and the mean total glance time off road were significantly lower with the rotary interface compared to the other designs (glances: dial vs. rotary $Z = -2.94$, $p < .01$, colour vs. rotary: $Z = -3.06$, $p < .01$).

Table.1. Total glance time by control position and control (task) type, means (sd)

Control position	Colour	Dial	Rotary
High	13.16 (1.60)	12.42 (2.90)	3.57 (2.81)
Low	15.33 (2.52)	12.44 (0.88)	1.50 (1.48)

Most of the subjects in the Low group tended to keep the number of glances off road minimal in the trials with the rotary interface. One subject in this group chose this strategy of visual behaviour before the rotary interface trial started and made no glances at all at the controls. The rotary control had significantly more efficient shape coding and method of use than the other controls and this presumably led to fewer glances in both groups with this interface. Also the excursions off road may have affected the visual behaviours of the subjects in the High group due to the rise in the level of experienced risk.

2.2.3 Assessments of task load and experienced risk

There were no significant differences between groups, except that the experienced risk while using the colour interface was reported significantly higher in the Low group ($M=79.17$, $SD=14.97$) than in the High group ($M=53.33$, $SD=15.38$, $Z=-2.25$, $p<.05$). Compared to the rotary interface, the experienced risk was rated significantly higher at the beginning of the trials and also after practice with the colour interface (start: Z=-2.05, p<.05; end: Z=-2.71, p<.01) and with the dial interface (start: Z=-2.55, p<.05; end: Z=-2.54, p<.05).

2.2.4 Discussion

Although there was an expected difference on the total glance times between the control positions with the rotary interface, this effect was not statistically significant. This could have been due to small sample size and the additional cautiousness of the subjects in the High group who drove off road before the rotary trial. The rotary interface had significantly more efficient shape coding and method of use for non-visual use than the other interfaces, and as hypothesized, this led to fewer glances in both groups with this interface.

3 EXPERIMENT 2

Experiment 2 was organized in order to examine the questions raised by the results of the first experiment. In addition, the moderating effects of speed and cognitive demand of the secondary task on the visual behaviours of the drivers were examined in a similar experimental design as in the first experiment. However, this time only the rotary interface was taken under closer investigation.

3.1 Experimental design

Independent variables in the experiment included the vertical position of the controls which varied between groups, the speed limit zone (20-40 km/h [Slow] and 60-80 km/h [Fast]) which varied within groups and the cognitive load of the secondary task which varied in the tasks of the last trial.

3.1.1 Subjects

16 subjects, eight men and eight women, were recruited via the same e-mail lists as in the first experiment. They were again divided into two balanced groups, High and Low. All of the subjects had a driving license and their driving experience varied between 1 000 and 100 000 km. The subjects' ages varied between 20 and 26 years (M=22.38, SD=1.96).

3.1.2 Tools and environment

The second experiment was conducted in the same environment and with the same tools as in the first experiment. However, this time the driving scene was larger, of size 160 cm x 93 cm, and both speedometer and rpm meter were projected in to the lower part of the driving scene. In the practice trial, the environment was a racing-type looped track and in the following trials the same track was driven as in the first experiment.

3.1.3 Procedure

After collecting background information, the first trial was driven without any secondary tasks for practice. In the second trial, the secondary task was an easy one-position task (total of 14 tasks), in which the subject chose a position of 0, 1, or 3 with the rotary interface as instructed. In the third trial, the secondary task (total of 10 tasks) was to select the right combination of the positions 0, 1, and 3 (e.g., 101310) as instructed. Difficulty of the secondary task varied between 2 to 6 digit set sizes and there were two tasks per digit set size. Basically, this task required keeping in mind the instructed digit set, remembering the last position of the switch, selecting the right direction to rotate and counting numbers downwards or upwards. The digits were aurally given in a randomized order in predefined parts of the road. The same basic instructions for the tasks were given for the subjects as in the first experiment. Practice with the easy secondary tasks included tasks with digits 0, 1, and 3, while the practice with the demanding secondary tasks included tasks with digit sets of sizes 2, 3, 4, and 6. Controlled variables in the experiment included the effects of track learning (different tracks were used in the practice and in the following trials, driving directions varied within a group), order effects (orders of secondary task instructions and driving directions were randomized within a group) and driving experience which varied within a group and was balanced between the groups.

3.1.4 Data analysis

Video scoring was made afterwards frame-by-frame by scoring glances and total glance times off the driving scene, secondary task errors (wrong selections) and driving errors during the secondary task (from the start of the instruction to the completion of the task). A driving error was defined to occur if the visible blue bonnet of the vehicle covered a white lane marker on the road or if the speed of the vehicle went off the defined speed zone. The non-parametric statistical Wilcoxon Signed-Rank Test and Mann-Whitney U-Test were again used to analyze the statistical significance of the differences between and within groups.

3.2 Results and discussion

3.2.1 Driving errors and selection task errors

There were no significant differences in the number of speed or lane maintenance errors between groups with different vertical positions for the controls in either trial. However, a significant effect of speed zone was found in the mean number of driving errors ($Z=-3.26$, $p<.001$). The mean number of driving errors in the Slow group (20-40 km/h) in the trial with the easy secondary tasks was 6.00 ($SD=4.34$) whereas in the Fast group (60-80 km/h) the mean was 16.50 ($SD=5.76$). In the trial with the demanding secondary tasks, the mean number of driving errors in the Slow group was 2.13 ($SD=1.46$) while in the Fast group the mean was 15.00 ($SD=9.17$). There was also a significant effect of digit set size on the number of driving errors. During the 6 digit tasks the number of driving errors was significantly greater than during the 2 digit ($Z=-2.00$, $p<.05$) or the 3 digit ($Z=-2.21$, $p<.05$) tasks (see Figure 2). This difference was significant with fast speeds, but not while driving slowly. The effect of digit set size was also more profound on speed maintenance; there were no significant effects on lane excursions alone. This is in line with other research on mental workload's effects on driving performance (e.g., [13]). However, the finding could also be simply addressed to the longer task completion times with the 6 digit tasks. Glances off road during secondary tasks and the driving errors did not seem to be related. Driving errors with eyes on the driving scene ($M=2.69$, $SD=3.20$) were significantly more common than with eyes off road (M=0.69, SD=.95, Z=-2.81, p<.01) during the secondary tasks.

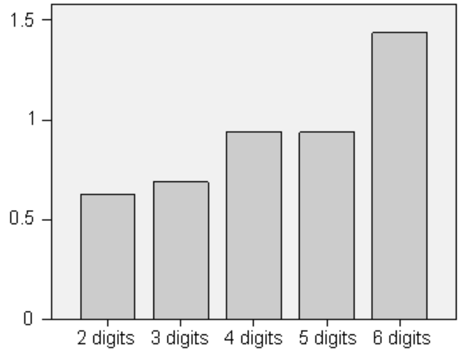

Fig.2. Mean number of driving errors (speed maintenance errors and lane excursions) during a secondary task by digit set size

There were no significant effects of control positions or speed zones on the number of secondary errors in either trial. Only four secondary task errors were made in the trials with the easy secondary tasks (224 tasks). In the trial with the demanding secondary tasks, there was a significant difference in the mean number of selection task errors between the 6 digit set tasks and the other tasks (e.g., 5 digits: 0.19 (.40), 6 digits: 1.25 (.68), Z=-3.31, p=.001).

3.2.2 Visual behaviour

Glance lengths varied from 0.20 to 1.56 seconds, except of one glance of 4.00 seconds in the High-Slow group. The dashboard's vertical position had a significant effect on the number of glances and total glance times with the demanding secondary tasks (TGT: Z=-6.30, p<.05; glances: Z=-2.27, p<.05; see Figure 3). In the Slow group, the differences between different dashboard positions in this trial were significant, but not in the Fast group. During the easy secondary tasks, glances off road were more common in the Slow group (M=21.50, SD=13.47) than in the Fast group (M=6.75, SD=3.92, Z=-2.11; p<.05; TGT: Z=-2.10, p<.05).

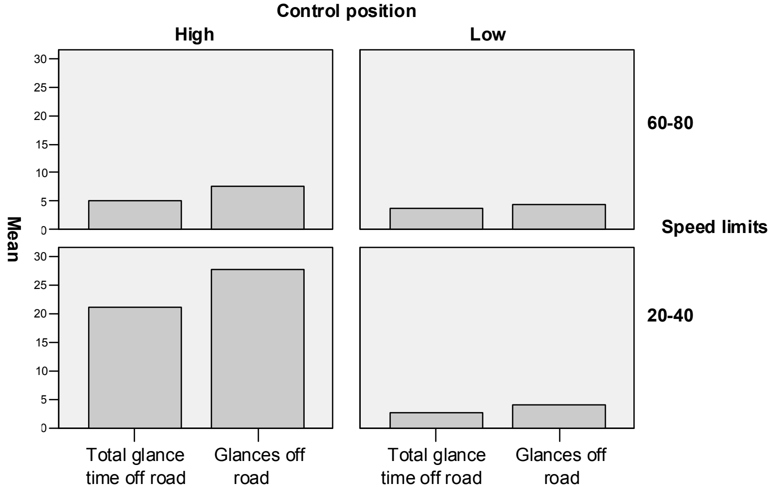

Fig.3. Interaction effects of the control's vertical position and driving speed on the number of glances and total glance time with the demanding secondary tasks

The effects of secondary task's cognitive load, speed, and the vertical position of the controls had a clear interaction. The increase in the attentional load led the subjects in the Low group to adopt a strategy of keeping eyes more on the road. In the Low group, the mean number of glances was 10.88 (10.13) in the easy task condition while in the demanding condition the mean was 4.25 (SD=4.30, Z=-2.37, p<.05, TGT: Z=-1.96, p=.05). However, keeping eyes on the road did not guarantee a success in the driving task if their attention was focused on processing the secondary task. This time the effects of the control's vertical location became visible, but only when accompanied with low driving speeds and/or high cognitive load.

4 GENERAL DISCUSSION

In line with prior research, the results suggest that there are several factors affecting the visual behaviour of the driver in dual-task situations. It is evident that only a few of these factors are related to the physiological aspects of human being, such as the time required for shifting gaze to controls while the eccentricity of the controls from the normal line of sight grows [3]. Control's poor shape coding can make the use of controls difficult or even impossible without visual attention. In addition, the demands of the driving task, such as traffic situation [11], road width [14], or driving speed as seen in the current experiments, may have an effect on driver's visual behaviour. Here, also the increase in the cognitive load of the secondary task placed more demands for the total task at hand and led the subjects with the lower position for the dashboard controls to adopt a strategy of keeping eyes more on the road. In these particular experiments, the absence of kinetic feedback on accelerations and the relatively small view on the driving scene may have enlarged the effects of the vertical distance of controls as well as the demands of the total task.

However, the results also suggest that visual attention is not the only form of attention that must be divided properly between tasks in order to secure safe driving. The substantial cognitive load of the secondary task affected driving performance, in particular speed maintenance (see also e.g., [13]), even if the subject kept eyes on the road. Overall, all of the aforesaid factors may affect the level of experienced risk and task difficulty the driver perceives while completing secondary tasks. We argue that this perception is one of the key factors directing driver's behaviour (see [9]). Thus, the behaviour of driver in realistic dual-task situations is more complicated than can be modeled by concentrating merely on the physiological aspects. Foremost, the results demonstrate the active role of the driver in evaluating task demands and adapting behaviours accordingly in dual-task situations while driving.

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