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DESIGN AND EVALUATION OF MULTIFUNCTIONAL GEARSHIFT FOR VEHICLE SETTINGS CONTROL THROUGH COGNITIVE ERGONOMICS TECHNIQUES

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ABSTRACT - An innovative concept of HMI has been developed to enhance the control of vehicle settings (gear, driving mode, cruise control, car height, suspension hardness and HMI graphic features) through a single device integrated in the gearshift, and a head-up display. Prototype variations of this HMI concept have been evaluated in a driving simulator, in order to assess their influence on driving performance, mental workload and user's emotional response. These aspects have been previously proved to be related with risk situations and driving safety, and are used to validate the conformance of the design with current initiatives of intelligent transport.

The concept of a multifunctional single control responds to the ergonomic principle of reducing complexity of user interfaces. The two dimensional movement allowed by the gearshift may be combined with a small number of buttons to provide rapid access to a high amount of functions and options, using a established navigation model for users of new technologies. Other principles from the field of Cognitive Ergonomics have been considered in the design of the head-up display and the navigation procedure through menu options, in order to reduce time consumption in the HMI operations, minimize error risk and keep a safe mental workload level. Anthropometric and biomechanical characteristics of users population have been likewise considered in the design of the gearshift and its navigation buttons, in order to assure a quick access and comfortable handling, and to prevent accidental operations by involuntary push of buttons or incorrect manipulation.

Driving performance is evaluated in simulator trials by measuring longitudinal and lateral control of the vehicle, comparing the results in the HMI manipulation context with the baseline of driving in different workload contexts. Mental workload and emotional response have been evaluated with multivariate measurements, through performance measurements, psychophysiological variables and subjective questionnaires. These tests provide a holistic view of the impact of this HMI concept on safety, and scientifically validated criteria to determine the best design options between the variant elements in the prototypes.

INTRODUCTION

Multifunctionality and multimodality is a growing trend in HMI development. As new functions are introduced to adjust motor settings, infotainment systems, cabin environment, driving assistance systems, etc., new solutions are sought to keep low levels of complexity of the interfaces, so that safety be not degraded by driver's mental overload. To achieve this, buttons, wheels and other controls are gathered in multifunctional devices like BMW iDrive® or Audi's MMI®, embedded in adaptable touchscreens, or moved to the steering wheel, thus multiplying the number of functions that may be controlled with one device. Another strategy is to make the machine communicate with the user in a more natural way, through multimodal interaction (1). Haptic modality is specially suitable when action and perception are simultaneously required, since touch is the only sense that can provide this simultaneity (2).

With this strategy in mind, a new concept of HMI has been developed. This system integrates various functions in a multifunctional gearshift. The gearshift lever allows a good haptic interaction, including kinaesthetic feedback of the movements that are being performed. The lever is used as a joystick with buttons, and the system information is displayed in a console screen and a Head-Up Display (HUD). This HMI concept has two variants, based on different navigation strategies. In both cases, menus, symbols and use procedures have been designed following principles from the field of Cognitive Ergonomics, in order to reduce time consumption in the HMI operations, minimize error risk and keep a safe mental workload level. Buttons size and location, as well as the shape of the joysticks, have been defined according to anthropometric characteristics of user population (3), in order to assure a quick access and comfortable handling, and to prevent accidental operations by involuntary push of buttons or incorrect manipulation.

These concepts have been previously analyzed using heuristic techniques (4). In this paper we present an experimental evaluation, to determine their potential impact on road safety and affective influence.

METHODS

Product description

Two prototype models of the HMI have been compared (see Figure 1). Each model consists of one joystick and two displays: a console or head-down display and a head-up display (HUD). By default, joystick movements along the Y-axis (left-right) switch between automatic and sequential manual gearshifts (AGS and MGS, respectively), and movements along the X-axis (forward-backward) are used to shift a gear in either of these modes. The gearshift mode and state are permanently displayed on the console screen. Advanced functions as Adaptative Cruise Control (ACC), Frontal Collision Warning (FCW), Speed Limit (SL), Driving Mode (DM) and Suspension Adjustments (SA) may be controlled by the system. To access these functions it is necessary to push the buttons on the joystick, and the information of advanced functions is shown on the HUD. DM and SA can be accessed only in static situations, while the rest of functions can be adjusted on road.

Figure 1. Multifunctional gearshift: Mobile model (left) and Sphere model (right).

Figure 2. Driving simulation.

Each model of the multifunctional gearshift manages these advanced functions in a different way. The model “Mobile” has a hierarchical menu that can be navigated through by joystick strokes and pushing the “ok” or “cancel” buttons on the joystick, roughly like in a cellular phone or a similar device. The model “Sphere” shows a sphere on the HUD when the button of the joystick is held, and this sphere can be virtually “rolled” through joystick strokes to select the functions and their adjustments.

Experimental procedure

The tests were conducted using a frame with an adjustable and Beta Research’s BR1050 driving simulator. The prototypes were assembled to the frame and connected by a CAN Bus to a PC. The console and HUD were simulated with two 8,4-inch screens in front of the user, that did not conceal the image of the road projected by the driving simulator (see figure 2).

21 Spanish drivers (10 women and 11 men) between 25 and 40 years old participated in the experiment. After a brief training (no participant had a prior knowledge of how the HMI worked) every participant tested both models. The test consisted in driving a road scenario during approximately 10 minutes, in which at certain times, secondary tasks to be done with the HMI were requested. The instructions were written in messages that popped up on the screen, and read aloud by a voice through the loudspeakers of the laboratory.

Secondary tasks were requested in low demanding driving conditions (curves were gentle and there were no obstacles. The vehicle had to be stopped to operate DM and SA). These conditions are representative of the situation in which the functions may be used, since drivers have an adaptative behaviour, and subsidiary tasks are skipped or delayed when demands increase (5). In this experiment the chief interest was to evaluate the effect of these design factors, so a baseline low demanding scenario was used to prevent other external effects. Pilot experiments showed that some drivers tended to feel too confident in the simulator, and exceeded safe speed levels even when no secondary tasks were being performed. This was a source of important variability in the test conditions, so it was decided to impose a safe limit of vehicle speed (60 km/h), in order to ensure that the conditions when the HMI was used were similar from one user to another.

Variables and analysis

During the tests, task performance and physiological variables of the user were registered, in order to have objective indices of the system usability and user emotions, mental workload and arousal. These measurements were complemented with questionnaires after the task, aimed to have the perception of users.

Performance of the HMI tasks was assessed by operation time and errors in the completion of the requested tasks, often used as indicators of workload (6). Driving performance has been assessed by longitudinal and lateral control of the vehicle (7), for which steadiness of vehicle speed and number of lane departures were recorded by the simulator.

Becker's Meditec's Varioport was used to measure phsychophysiological variables: facial EMG of the zygomatic and corrugator muscles (ZEMG and CEMG, respectively), Heart Rate (HR) and Galvanic Skin Response (GSR). Facial EMG is related to the valence of stimuli: pleasant stimuli increase zygomatic activity (ZEMG), whereas unpleasant stimuli raise the level of corrugator activity (CEMG). On the other hand, HR and GSR are linked to orienting response or emotional arousal (8). Specifically, Heart Rate Variation (HRV) is used to evaluate mental load in driving, as HRV is reduced when a user performs a task that implies an effort (9). These variables were normalized with respect to a baseline value, that was the average value in the five seconds previous to all tasks, when the user is just driving, not using the HMI.

Participants filled three questionnaires after each test. The first was a subjective rating in a 5-point Likert Scale of the following qualities of the HMI: *innovative*, *comfortable*, *complex*, *coherent*, *elegant*, *sporty*, *intuitive*, *precise*, *intelligent*, *functional*, *ergonomic* and *personal*. This reduced vocabulary, gathered from a vocabulary analysis of automotive journals and forums, was analysed with Kansei Engineering techniques to extract the principal components of the HMI semantic universe and the position of each model in that space.

Then the functions of the HMI were subjectively evaluated in two ways: (a) a function-by-function rating of the "adequateness" of their design in a 5-point scale; and (b) asking the users which function they considered as the "most adequate" and the "least adequate" ones.

All measurements were statistically analysed using a repeated measurements experimental design, in order to detect the differences between the models.

RESULTS

Performance in HMI Tasks

Time consumption depends chiefly on the task: the most time-demanding task is SA, and the time that it consumes is significantly greater than for MGS, AGS, DM and SL ($p < 0.05$). This may be due to the fact that SA is the first action that the user does in the driving scenario, just after starting. The least time-demanding tasks are AGS and MGS; between them, AGS consumes less time than MGS ($p < 0.05$). Time consumption is not generally different between HMI models; but there is a significant interaction between task and model (p-value < 0.05). This interaction affects DM, that consumes more time in the Mobile model, as shown in figure 3.

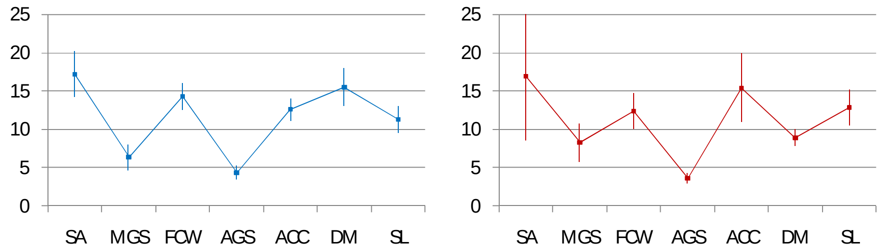

Figure 3. Time consumption for Mobile (left) and Sphere (right).

Table 1. Average successes, slips and failures of users performing the 13 tasks.
Asterisks (*) mark the results that are significantly different between M-SHIFT models ($p < 0.05$)

	Mobile	Sphere	Both
Successes *	11.7	10.2	10.9
Slips *	0.9	2.3	1.6
Failures	0.4	0.5	0.5

The number of successes and slips are significantly different, depending on the HMI model (p-value < 0.05). Table 1 shows the averages of these scores for both interfaces. It may be observed that the number of successes at the first trial is significantly higher for the Mobile model, and the number of slips is significantly lower. Nevertheless, the number of successes is relatively high in both cases, and there are no differences in the number of failures, that is always low.

Driving Performance

In two of every three tests, users drove off the lane one or more times, and the average number of lane departures was 1.5 per test. However, most lane departures occurred in normal driving, regardless of the HMI. Only 16% of lane departures occurred when the driver was performing the requested tasks with the HMI, and if just these cases are considered, the average number of lane departures decreased to 0.2.

Due to the speed limitation longitudinal control was very high. Figure 4 shows an example of the vehicle speed function. The standard deviation of speed during the first 1500 m, the baseline condition when no on-road HMI task had been requested yet, was 0.35 km/h in average. In 48% of the trials, drivers maintained the top speed when they were using the HMI (except when they were requested to stop the vehicle). But in average terms, speed deviation raised to 0.66 km/h in the secondary-task conditions, and this increase of speed deviation was significant ($p < 0.05$ in a pairwise comparison between the baseline and secondary-task

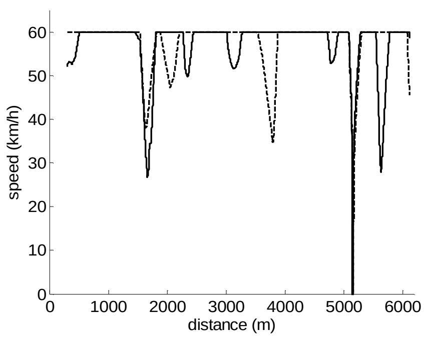

Figure 4. Example of vehicle speed during the test.
Solid line: Mobile model, Dashed line: Sphere model.

Table 2. Statistical differences in psychophysiological signals depending on the action.

	AGS	MGS	DM	SA
ACC	CEMG	CEMG	CEMG/HRV	CEMG
SL	HRV	CEMG/HRV	HRV	CEMG/HRV
FCW		CEMG	CEMG/HRV	CEMG

conditions).

The number of lane departures and speed deviation (both in the baseline and secondary-task conditions) were also compared depending on the HMI model and the order of the test, but no significant differences were found for these factors.

Psychophisiological measurements

All physiological signals, normalized by the average driving condition, were statistically compared using the action and the HMI model as possible factors of variance in the results. Only the action showed a significant effect, in CEMG and HRV.

The differences depending on the action may be explained by defining two groups of actions: the group "A" is comprised by AGS, MGS, DM and SA; the group "B" by ACC, SL and FCW. The differences in CEMG, HRV and GSR are generally between actions of these two groups in the following manner:

(a) CEMG (i.e. the muscular activity related to negative emotions) is higher in the actions of group "B".
(b) HRV is higher (i.e. the mental effort is lower) in the actions of group "A".

These differences are shown in detail in Table 2. Actions of group "A" are represented in its columns, and actions of group "B" in rows: cells show in which variables are found the differences between each pair of actions of these groups. These results may be interpreted as advantageous for group "A".

The HMI model has no significant effect in this analysis, though there is a nonsignificant trend of lower CEMG levels (less activity related to negative emotions) for the Mobile model, but higher HRV (less mental effort) for the Sphere.

Semantic analysis

Table 3 summarizes the results of the semantic analysis. Five principal components explain individually more than 10% of variance in the ratings of the twelve "Kansei" adjectives, and the model with these components explained 79.6% of the total variance. When the scores of the original adjectives for each component are examined, a relation between these components and design aspects of the HMI may be found, say: "usability", "style", "performance", "simplicity" and "elegance". The ratings in the "usability" and "performance" components are higher for the Mobile Model, what means that it is better evaluated in these aspects.

Table 3. Summary of the semantic analysis. The second row 'Expl. variance' shows the variance of original answers that is explained by each principal component. The last row 'Differences' shows the results of the t-test performed to the values of these components depending on the HMI model. Central rows are the scores of original adjectives for each component (using a Varimax rotation).

Design aspect	Usability	Style	Performance	Simplicity	Elegance
Expl. variance	19.7%	19.3%	17.5%	12.4%	10.6%
Comfortable	0.86	0.06	0.26	0.20	0.01
Ergonomic	0.71	0.24	0.07	0.10	0.31
Intuitive	0.67	0.30	0.04	0.33	0.31
Sports	0.03	0.88	0.01	0.12	0.21
Personal	0.30	0.81	0.18	0.23	0.15
Innovative	0.44	0.62	0.21	-0.31	0.04
Precise	0.26	-0.05	0.86	0.00	0.16
Intelligent	-0.05	0.21	0.86	0.25	0.17
Functional	0.37	0.41	0.59	0.30	-0.04
Complex	-0.25	-0.05	-0.24	-0.83	0.10
Coherent	0.24	0.31	0.15	0.57	0.49
Elegant	0.22	0.20	0.22	-0.07	0.84
Differences	Greater in Mobile (p = 0.00)	None (p = 0.79)	Marginally greater in Mobile (p = 0.07)	None (p = 0.42)	None (p = 0.32)

Subjective function evaluation

Table 4 summarizes the results of the subjective function evaluation. Functions are sorted in descending order of average "adequateness" rating (first group of columns). It may be observed that the average ratings in the Mobile model was generally higher than in the Sphere model, and this difference was statistically significant for AGS, DM, SL and FCW ($p < 0.05$ in a Friedman test).

The second and third group of columns show the frequency at which every function was qualified as the "most adequate" or "least adequate". The columns sum more than 100%, because participants used to mention more than one function as the best or the worst one. The "Sig." columns are the result of Chi-square tests, that determines whether the answers were different depending on the HMI model. The only significant difference ($p < 0.05$) was that SL

Table 4. Summary of the analysis on subjective function evaluation per model (M = Mobile; S = Sphere).

	Average rating			Best function			Worst function		
	M	S	Sig	M	S	Sig	M	S	Sig
AGS	4.6	4.1	0.04*	57%	57%	1.00	0%	0%	1.00
MGS	4.6	4.1	0.10	52%	52%	1.00	0%	10%	0.16
ACC	4.1	3.9	0.37	14%	29%	0.32	24%	24%	1.00
DM	4.3	3.7	0.02*	14%	19%	0.71	43%	33%	0.62
SL	4.1	3.3	0.00*	5%	5%	1.00	14%	57%	0.02*
SA	3.9	3.4	0.14	14%	19%	0.71	48%	43%	0.82
FCW	3.9	3.2	0.02*	5%	5%	1.00	43%	57%	0.51

adjustment was more frequently mentioned as the least adequate function in the Sphere model.

DISCUSSION

Two prototypes of multifunctional gearshift have been developed as a new HMI concept. Their usability, potential impact on road safety and affective influence on user have been evaluated, and both models have been compared in order to detect the strong and weak points of each design.

Secondary task performance shows that the evaluated prototypes have a good usability standard. Drivers succeeded to complete the tasks in the first attempt 83.8% of the cases, and failed only in 0.4% of cases. Time consumption is acceptable for most functions, though improvable in some cases. Thresholds between 10 and 15 seconds have been suggested as the longest task completion times that could be undertaken in stationary conditions (vehicle stopped), before driving is unquestionably degraded; these reference levels can be raised to 13 and 20 seconds when the vehicle is moving (7). In the experiments that have been conducted, AGS and MGS are well under this these thresholds for both HMI models, as well as DM in the Sphere model. FCW, ACC, and SL are in an acceptable range, but could be improved in both models. DM in the Mobile model, and SA in both models, are in the limit or over the threshold; however, these actions are conceived to be used only when the vehicle is stopped; therefore safety is not put at risk in terms of time demand. Moreover, these are the values for naïve users; heuristic analyses of these HMI concepts reveal that an experienced user could perform the tasks in less than 5 seconds (4).

Results on driving performance also indicate that these HMI may be improved, but they provide an acceptable safety level. Drivers usually maintained the top speed when they were not using the HMI, with a standard deviation of 0.35 km/h. To perform the requested tasks, they usually slowed down the vehicle momentarily, thus speed deviation increased to 0.66 km/h. On the other hand, while lane departures were observed in two of every three trials, only a 16% of these cases coincided with HMI handling. Therefore, although the use of these models of HMI altered speed control, it did not appreciably increase the risk of driving off the road. The conclusions drawn from these results are limited to the conditions of the test scenario. In this case the scenario had a low driving demand, and speed had been limited.

Psychophysiological and subjective evaluations confirmed that AGS and MGS were optimally designed, as had been observed with secondary task performance. These functions induced the lowest levels of negative emotional response and mental effort, and they were the best evaluated ones. This is an important result, because they are the primary functions of the HMI. DM and SA also caused relatively positive levels of the physiological signals, probably because they were operated in static conditions, but they were neither the best evaluated nor the most efficient ones.

Each model has its own advantages and shortcomings. The Sphere model is intrinsically more simple (4), and this may be the reason for a lower mental effort, as is observed in the physiological signals (though the differences are not significant). However, drivers had to correct their actions less frequently with the Mobile model, and some functions of this model were evaluated as more adequately designed; accordingly, a semantic analysis yields that the Mobile model was considered to be more usable, and to have a greater performance. This may be due to prior experience of users with the navigation strategies used in that model, similar to cellular phones or similar devices: although the interface is more complex and more steps are required to perform most tasks, user habits seem to compensate these theoretical drawbacks, and this may improve user judgements and performance, at least in the early learning phase.

In conclusion, performance, physiological and subjective measurements have been successfully used to gather coherent conclusions about the HMI concepts, that may be used to improve their design.

Future work

This methodology may be applied in future studies with other interfaces, for more complex scenarios, in more demanding contexts or risk situations, or with more variable test conditions in general. Other subjective or physiological techniques could be also applied, in order to see the coherency of results.

In this study, the interaction with the vehicle and the HMI were independent. The communication between HMI and simulator events will allow a more complex interaction. Complex, “intelligent” responses of the system, and other stimuli dependent of road events may be also elicited with the “Wizard of Oz” technique. This would allow a more natural interaction with the machine, as is sought with modern multimodal interfaces (10).

The population used in this study were young (25–40 year old) drivers. It would be also interesting to address the particular needs of other collectives, like elderly users, people with disabilities, etc., in order to see the effect of these technology products on performance, emotions and satisfaction.

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