Driver reactions on ecological driver feedback via different HMI modalities

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Abstract
Nowadays there already exists a large amount of driving-related information displayed in the dashboard and thus additional information concerning ecological driving might enlarge the workload of the driver further. This raises the question whether the presentation of additional ecologic information via the haptic channel is more efficient and comfortable for the driver compared to a visual presentation. Previous studies proved the impact of driver feedback systems on the reduction of fuel consumption. However, most of the studies only dealt with visual displays. Thus in the present study a visual, a haptic, and a visual-haptic interface were designed for an acceleration and a gear shift advice system. Subsequently their impact on the acceleration and the gear shift behavior of the driver as well as their subjective acceptance were compared. Results showed that especially the combination of the visual and haptic modality led to the fastest reaction times and smallest deviations from the optimal acceleration and gear shift behavior. However, concerning the acceptance participants preferred the visual display.
Keywords:
HMI, ecological driver feedback, information modality, user acceptance, driving simulator

Introduction

One of the aims of the European integrated project eCoMove (EU FP7) is to dynamically advice drivers how to drive eco-efficiently by influencing driver's acceleration, deceleration, and gear shift behavior (Eikelenberg et al. 2011). In this context an important task is to design the most suitable, efficient and user-friendly Human-Machine-Interaction (HMI) strategy for this ecoDrivingSupport information to be implemented into the eCoMove demonstrator vehicle. Especially the choice for one or more communication channels (e.g. visual or haptic) is crucial. Within the process of eCoMove user-centered HMI design approach the present study was conducted.

Previous studies dealt with the impact of driver feedback systems on the reduction of fuel consumption. Hence, van der Voort, Dougherty & Maarseveen (2001) introduced a driver-feedback system, which helped to save 16% of fuel compared to driving without such devices. Wu, Zhao & Ou (2011) even found 22-31% overall gas savings for a fuel-economy optimization system (FEOS) which displayed the optimal acceleration/deceleration profile to the driver. Another study from the NHTSA (Manser et al., 2010) compared two different Fuel Economy Driver Interface Concepts (FEDIC) to reduce fuel consumption and found that a visual feedback with fuel information (average fuel consumption) led to more fuel-efficient driving than a device which gave visual feedback on the fuel saving behavior or no device. Nevertheless, participants glanced away from the street more often when driving with FEDIC-devices. Birrell and Young (2011) also showed positive effects of visually presented smart driving information about the amount of excessive acceleration and deceleration in a simulator study. Additionally, they could not find any negative effects such as higher workload or distraction when driving with smart driving information systems. Still, integrating more and more visual information into the dashboard bears the risk that drivers divert their visual attention from the forward view too often. Thus Hallihan et al. (2011) researched the driver distraction of a hybrid-interface which helped the driver to improve fuel-efficacy. Results showed glance durations away from the road which lasted longer than 1.6s when drivers glanced to the interface and the speedometer. Moreover, numerous studies have dealt with and showed negative impacts of distraction by visual in-vehicle information systems (IVIS), for example within the EU Project HASTE (Santos et al., 2005, Hamish & Merat, 2005, Antila & Luoma, 2005, Engström, Johansson & Östlund, 2005). However, according to Wickens (2002) it should be easier for drivers to do two tasks at the same time using different modalities than sharing the same modality. One study in line with this assumption showed that speech-based interfaces for three different IVIS reduced the distraction caused by these systems compared to visual interfaces (Maciej & Vollrath, 2009). Another study by van Erp & van Veen (2004) demonstrated that a tactile navigation display reduced the workload of the driver compared to a visual display especially in situations with high workload. In conclusion, the results support the idea that haptic or visual-haptic eco-feedback might speed up driver reactions and at the same time reduces the distraction potential compared to visual feedback alone.

With regards to the type of eco-advice, Ericsson (2001) found nine driving pattern factors which had substantial effects on fuel consumption. Four of these are connected to acceleration and another three refer to gear shift behavior. Consequently some authors researched the impact of an active accelerator pedal on the reduction of fuel consumption and emissions. Várhelyi et al. (2004), for example, reported positive effects, while Larsson & Ericsson (2009) only found small reductions in fuel consumption depending on the route characteristics. Furthermore, measurements have proven that gear-shifting behavior can influence fuel consumption significantly. Changing gear from 3rd to 4th can reduce fuel-consumption by 19% and from 4th to 5th gear by 25% (Dhaou, 2011).

Considering the reported studies, the goal of this study was to compare a visual, a haptic and a visual-haptic acceleration and gear-shift driver feedback system concerning their impact on fuel consumption and driver acceptance. The modalities were tested on an acceleration advice system and a gear shift advice system. In addition to driving behavior indicators of the acceptance of the different modalities were measured.

Method

In order to examine the research questions a study with the motion based dynamic driving simulator of the German Aerospace Center (DLR) was conducted. The motion system of the simulator is characterized by a hexapod system with the cabin hanging in below the upper articulations. A high-quality projection system provides the visualization of the surrounding environment and traffic. Besides the forward view the driver can also observe the simulated traffic behind him by the rear-view mirror on a screen and by LC-displays in the lateral rear mirrors. For a realistic overall impression the direct environment of the driver is very important. Therefore a complete vehicle has been integrated into the cabin with which the driver is “driving” the simulator. For this purpose the actions of the driver are transmitted via CAN-Bus to the simulation computer, vice versa the simulation system controls the instruments inside the cockpit, which for example inform the driver about his current speed. All inputs and actions made by the driver, from braking over steering to operating the radio, can be recorded and analyzed.

Experimental Design

The study consisted of the two independent variables of driving scenario (six different target speeds) and the modality of the assistance systems (visual, haptic, visual-haptic).

The participants drove on a rural and urban road and had to accelerate to different speeds. The trip consisted of six sections with different speed limit signs. In each section the participants started with a velocity of 0 km/h and had to reach a target speed as precisely as possible that was displayed by speed limit signs. Table 1 shows the different target speed-scenarios. In three of the scenarios the drivers had to accelerate to only one target velocity followed by a phase of constant driving. Another three scenarios consisted of one target velocity followed by a phase of constant driving and another target velocity (see table 1 scenarios 4-6). These scenarios were used to control a potential effect of the start velocity on the results.

Table 1 - Target speed scenarios

Scenario	Target speed
1	Acceleration from 0-30 km/h
2	Acceleration from 0-50 km/h
3	Acceleration from 0-100 km/h
4	Acceleration from 0-20 km/h-30 km/h
5	Acceleration from 0-30 km/h-50 km/h
6	Acceleration from 0-50 km/h-100 km/h

During the driving task the participants were assisted by acceleration and gear shift advices through a visual, a haptic or a visual-haptic interface. The acceleration advice was a continuous feedback about the deviation from the optimal acceleration profile. In comparison, the gear shift advice was discrete and informed the driver about when and in which gear to change. The acceleration advice was dependent on gear and velocity. For example, while driving in the 1st gear, the target/optimal acceleration was 2m/s^2 whereas driving in the 5th gear resulted in a target acceleration of 0.7m/s^2). In addition to the acceleration advice the gear shift advice was designed to avoid driving with inefficient low gears and high rotational-speed ranges. Therefore the rpm-limits were also specified depending on the chosen gear ranging from 1900rpm (1stgear) to 1600rpm (5thgear). The visual advices were presented in the middle of the dashboard. Figure 1 illustrates the visual advices.

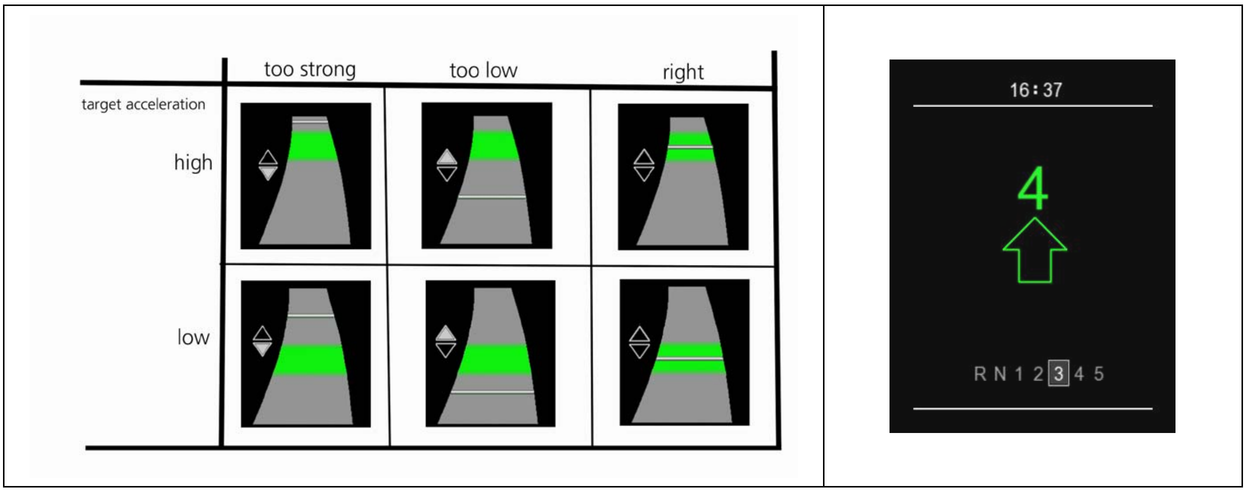

Figure 1 - Visual acceleration and gear-shift advice presented in the dashboard

The visual gear-shift recommendation consisted of a green arrow pointing upwards or downwards and a green digit representing the target gear. The visual acceleration advice for acceleration / deceleration showed the target acceleration (green range) as well as the actual acceleration (grey line). The driver accelerated too much if the line was above the green range and not enough if the line was below the green range. When both elements were in the same position the acceleration was right. The haptic acceleration advice was presented as a counter pressure on the acceleration pedal. The haptic gear shift advice was featured with a double tick on the acceleration pedal which was repeated twice with intervals of 1.5s. The visual-haptic advice consisted of the combination of both individual modalities.

The gear shift advice was prioritized higher than the acceleration advice regardless of the modality. This was due to the impossibility to simultaneously present a haptic continuous pressure (acceleration advice) and a haptic double tick (gear advice). Therefore advices were presented sequentially within all modalities.

The study was carried out using a within subjects design. Thus, each participant experienced the three advice modalities and within each modality the six target speed scenarios. The order of the advice modalities was counter balanced across all participants and the order of the scenarios was randomized within each modality.

Participants

Twenty-four participants (12 male, 12 female) took part in the study aged between 22 and 70 years (M = 41.8, SD = 16.7 years). The participants were randomly drawn from the DLR test driver database that contains more than 850 participants of all ages and different driving characteristics. Half of the participants reported a medium to low annual mileage (between 3000 and 12000 km/year), 29.2 % a medium to high annual mileage (between 12000 and 20000 km/year), 8.3 % a high annual mileage (more than 20000 km/year) and 12.5 % a low annual mileage (less than 3000 km/year).

Results

Acceleration Behavior

Within a preliminary analysis of the results it became apparent that during the scenarios 4, 5 and 6 a large part of the participants already accelerated before reaching the second speed-limit sign. More specifically, this was the case in 72 % of the drives with visual, in 53 % with haptic and in 70 % with visual-haptic advices ($\chi^2(2) = 6.2$, $p < .05$). The distance to the speed-limit sign, at which these participants initiated their acceleration maneuver showed a significant difference between the advice modalities ($F(2,24) = 13.5$, $p < .001$, $\eta^2 = .52$). They accelerated around 35 m (SD = 1.6) in front of the sign with the visual, 18 m (SD = 6.9) with the haptic and 21 m (SD = 12.0) with the visual-haptic interface. This violation of the road traffic regulations and the pre-drive instructions resulted in an omission of some advices past the speed limit sign for some participants due to the velocity level. As a result, the second acceleration phase of scenarios 4, 5 and 6 was excluded from the calculation of the acceleration deviation. Thus, the first acceleration phase at the beginning of each scenario, the following phase of constant driving and the second section of constant driving of scenarios 4, 5 and 6 were considered for further analysis. Due to the exclusion of the second acceleration phase - scenarios 1 and 5 as well as scenarios 2 and 6 were comparable regarding starting and target velocity. Therefore the scenarios 5 and 6 were cumulated with the scenarios 1 and 2 respectively. Hence, the acceleration behavior was analyzed in scenarios 1 (30 km/h), 2 (50 km/h), 3 (100 km/h) and 4 (20 km/h).

During the acceleration phases a significant difference between the advice modalities could not be identified. In the phases of constant driving there was an interaction between modality and scenario ($F(3.4, 78) = 4.2$, $p < .05$, $\eta^2 = .155$). Thus in scenario 4 the deviation to the optimal acceleration level was significantly higher for the visual modality compared to haptic and visual-haptic advices both ranging at approximately the same error level. Figure 2 shows the mean acceleration deviations depending on the scenario and advice modality.

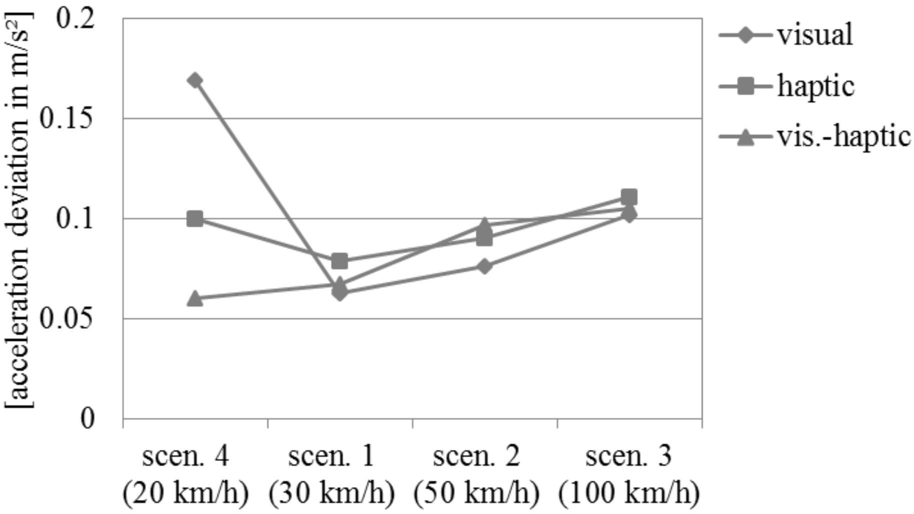

Figure 2 - Mean acceleration deviation during constant driving depending on scenario (scen.) and advice modality

Gear Shift Behavior

To answer the question of how fast the drivers followed the advice reaction times towards the advices were calculated. This was defined as the time between the onset of an advice and the time the driver started to move the gearshift to neutral. Since the whole range of gears (gear 1 to 5) was only used in scenarios of higher target speeds, data regarding the number of gear shifts and corresponding reaction times per scenario varied across scenarios. To obtain the same frequencies of the factor levels the reaction times of the scenarios 1 to 3 and 4 to 6 were aggregated per modality and gear shift, since both scenario groups contained the same target speeds. The result was the averaged reaction time for each advice, each gear and both scenario groups. There was a significant main effect for the factor gear ($F(1.7, 40.9) = 16.5$, $p < .001$, $\eta^2 = 0.42$) and a significant semi-disordinal interaction of the factors gear and advice modality ($F(3.5, 82.6) = 4.9$, $p < .001$, $\eta^2 = 0.18$). Thus the reaction times differed dependent on the gear that was chosen afterwards. In detail the participants reacted significantly slower when shifting into higher gears (especially the 5th gear) than when shifting into lower gears. Regarding the interaction the results showed that the difference in reaction times for the gear shifts also depended on the kind of advice modality that the participants had received. As Figure 3 shows, in lower gears the reaction times for all modalities were close together. However, when shifting into the fifth gear the participants reacted with the visual-haptic advice much faster than with both other modalities.

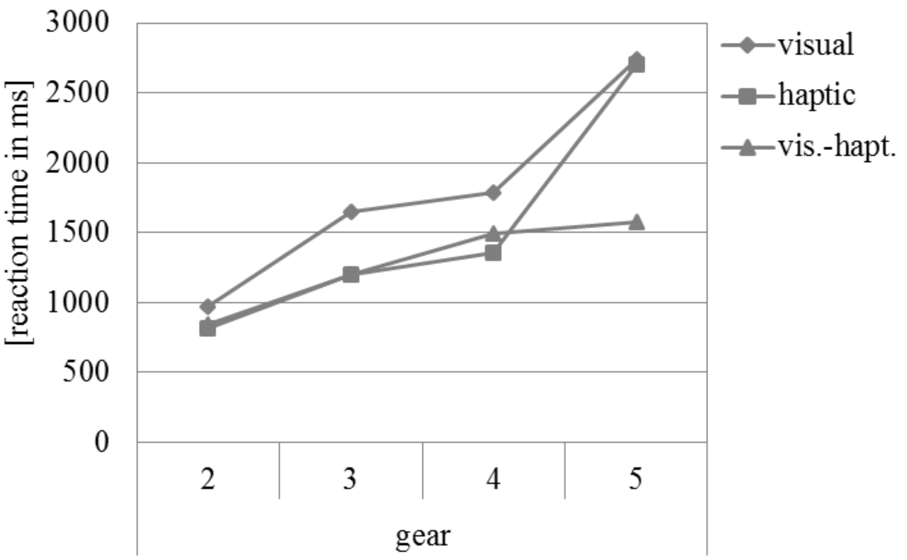

Figure 3 - Mean reaction times to the gear shift advice depending on gear and advice modality. Advices were given for shifts into the 2nd, 3rd, 4th and 5th gear.

Non-compliance with the advices was determined by summarizing all events in which advices were not followed by a gear shift behavior of the participants. The overall number of advices was 1069, from which 38 (3.6 %) were disregarded. To examine if some gears were ignored more often than others the ratios of disregarded vs. followed advices for the different gears were calculated. The results showed a significant difference between the gears ($\chi^2(3) = 47.7$, $p < .001$). All advices to shift in the 2nd gear were followed, 95.7% of the advices to shift in the 3rd and 97.2% to shift into the 4th gear. The 5th gear-advice was disregarded most often

since only 87.1 % of the advices were followed.
To examine if some advice modalities were disregarded more often than others the ratios of disregarded vs. followed advices were calculated for the advice modalities and a significant difference ($\chi^2(2) = 15.3$, $p < .001$) was found. 99.1 % of the visual-haptic advices and 96.5 % of the visual advices were followed. The haptic advice was disregarded most often since 93.6 % of the advices were followed.

Questionnaire Data

First of all, the three modalities were compared concerning the subjective workload using the DALI-Questionnaire (Pauzie & Pachiaudi, 1997). In general the haptic modality was rated less distracting than the visual and the visual-haptic modality ($F(1.9,43.1) = 11.0$, $p < .001$, $\eta^2 = .32$). Concerning the situational stress the visual-haptic modality was rated the highest ($F(1.9,44.2) = 4.8$, $p < .05$, $\eta = .17$).
Secondly, the participants were asked for their acceptance of the advice systems using a modified version of the Design-Use-Function Acceptance Scale (Kassner, 2011). The questions were split into two parts: nine items related to aspects of the design of the system (e.g. comprehension, learnability/intuitiveness) and usefullness (e.g. assisting, distracting) and were evaluated in terms of agreement by a five-point rating scale (1 = not at all, 5 = extremely). In the second part 3-5 items (depending on the type of advice) evaluated the functionality of the advice on a five-point rating scale (1 = not at all good, 5 = extremely good).The results give a clearer picture what specific properties of the different assistant systems resulted in an overall approval or rejection. Concerning the design of the gear shift advice the visual modality was rated most comprehensible by the participants ($F(1.6,36.9) = 5.5$, $p < .05$, $\eta^2 = .19$). In contrast the salience ($F(1.8,41.1) = 5.6$, $p < .01$, $\eta^2 = .20$) and the call for action ($F(1.6,36.3) = 5.7$, $p < .05$, $\eta^2 = .20$) of the visual modality of the gear shift assistant were rated significantly lower compared to the other two modalities. Similar results emerged regarding the design of the acceleration advice: the participants rated the salience ($F(1.7,39.6) = 3.5$, $p < .05$, $\eta^2 = .13$) and the call for action ($F(1.7,38.4) = 15.9$, $p < 0.001$, $\eta^2 = .41$) of the visual modality significantly lower than for the other two modalities. The analysis of usefulness ratings did not show any significant results. However, concerning the acceleration advice the differences of the mean distraction ratings between the visual modality and the haptic modality were significant ($F(1.5,33.8) = 3.4$, $p = .06$; $T(23) = 3.9$, $p = .001$, $d = 0.87$). Consequently the participants felt more distracted by the visual modality than by the haptic modality. Further they felt more precluded from driving their own style when they used the haptic modality in contrast to the visual modality ($F(1.5,35.0) = 3.2$, $p = .066$; $T(23) = -2.6$, $p < .05$, $d = 0.68$).
At the end of the study the participants were interviewed concerning their design preferences for the advice systems. The majority of the participants (45.8 %) stated that they preferred the

visual modality, 29.2 % favored the visual-haptic modality and only 2 participants (8.3 %) preferred the haptic modality. 16.7 % of the participants did not decide for any modality but stated it depended on the system (acceleration vs. gear shift advice). In most cases the participants reasoned their statements with aspects of pleasantness. More specifically, 41.2 % of the participants who preferred the visual modality did not feel comfortable with the haptic acceleration advice (23.5 % with the haptic gear shift advice). Some even described the haptic modality as annoying. Another 23.5 % felt less distracted using the visual advice systems. Two participants stated that when they used the haptic modality alone they were missing a visual feedback. On the other hand 37.5 % of the participants felt comfortable with the haptic modality at all, thus they stated they liked the haptic modality especially because they felt less distracted.

Discussion

The results of the study are summarized in Table 2. Results which show advantages of the modalities are marked with dark grey, disadvantageous results with light grey.
The visual advice was preferred by most of the participants, thus had the best acceptance scores, but had the worst results concerning the objective performance measures. The haptic modality did neither result in superior driving measures nor was it preferred by the users of the systems. However, concerning the subjective ratings of distraction, effort of attention and situational stress, the haptic modality was beneficial. The visual-haptic advice came off the best considering the results of the objective driving measures, but had some disadvantages concerning the acceptance similar to the haptic advice. In the following paragraphs the results will be discussed in more detail:
With regards to the acceleration behavior the participants started accelerating later when they saw a new speed-limit sign with the haptic and the visual-haptic advice. The counter pressure of the gas pedal probably prevented the participants from speeding up too early. This aspect might be beneficial for traffic safety aspects but it might also be one reason why the participants did not appreciate the haptic modality as much as the other modalities. Possibly they felt patronized. Furthermore, the deviation from the optimal acceleration profile in the 4th scenario (where the drivers had to maintain a speed level of 20 km/h) was smaller with the haptic and the visual-haptic advice, compared to the visual advice. Possibly this was due to the fast alteration of the advice to accelerate up to 20 km/h and the advice to maintain the speed, which could not be captured as fast over the visual channel as over the haptic channel. Apparently with the haptic support the participants got a more direct feedback to reduce the acceleration in order to maintain their speed. This led to faster reactions compared with the visual modality.

Table 2 - Overview of the study results

Advice Systems	Aspects of evaluation	Visual	Haptic	Visual-haptic
Acceleration Assistance	Initiation of acceleration in front of the speed-limit sign	35 m**	18 m	21 m
	Constant driving: deviation (m/s²) from the optimal profile (scenario 4, 20 km/h)	0.169**	0.100	0.105
	Acceptance – salience (mean)♦	3.67*	4.04	4.12*
	Acceptance – call for action (mean)♦	3.13**	4.04	4.33
	Acceptance – distraction (mean)	3.50	2.54	2.88
	Acceptance – preclusion (mean)	2.63*	3.38*	2.46
Gear shift Assistance	Reaction time (overall)	1.8 s	1.5 s	1.3 s*
	Reaction time (shifting in the 5th gear)	2.7 s	2.7 s	1.6 s**
	Percentage of disregarded advices	3.5 %	6.4 %	0.9 %*
	Acceptance – comprehensibility (mean)	4.58*	4.17*	4.29
	Acceptance – salience♦	3.92**	4.46	4.46
	Acceptance – call for action♦	3.96*	4.46*	4.25
Both - overall ratings	HMI-preferences after test drives	47.5	31.1	13.1
	DALI - effort of attention (average)	3.67	2.58**	3.54
	DALI – situational stress (average)	2.79	2.21	3.42**
	Overall acceptance – percentage of participants who preferred the modality	45.8 %	8.3 %	29.2 %

Considering the gear shift behavior participants shifted up faster with the visual-haptic advice especially into the 5th gear compared to the visual advice alone and disregarded fewer advices. Similarly to the acceleration advice the haptic modality seemed to ease a faster perception of the advices, because the drivers did not have to attend to the dashboard first. On the other hand the haptic advice alone was ignored too often. However, in the case of the combination of both advices the haptic modality might have drawn the driver attention to the visual display in the dashboard faster and therefore reduced the reaction time. These results suggest that the visual-haptic display combined the advantages of both stimuli by speeding the reaction time through the haptic part and improving the perceptibility and the compliance through the visual part. This was especially useful for shifts in higher gears where the most potential for

♦ Lower mean scores correlate with higher acceptance by the participants

*p<.05

**p<.01

improvements in ecological driving behavior exists.

Regarding the questionnaire data the majority of the participants favored the visual modality because it was less salient than the other two systems, not as “annoying” as the haptic modality and consequently easier to be ignored if necessary. Hence, the need for broad information about ecological driving behavior seemed to be smaller than the need for comfortable and undisturbed driving. Some also reasoned with the aspect of controllability meaning that they liked to decide themselves if they want to follow the advice of the system depending on the driving situation. This attitude reflects that ecological driving is neither the only nor the most important priority when driving a vehicle. However, still about one third of the participants preferred the combination of haptic and visual information. They reasoned that it was more salient and less distractive because they did not have to watch the dashboard all the time for advice. Also the analysis of the objective data showed that the visual-haptic advices helped most effective to save fuel. Possibly there is a connection between the preference of the visual haptic modality and a positive attitude towards “Green Driving Assistance Systems”.

The results of this study should be used to inform the design of fuel saving assistance systems. The visual-haptic modality resulted in the best driving results as well as good preference values (one third of the participants liked the combination of the modalities). If the assumption that those who like to be informed about environmental aspects by multiple channels are also the ones who have the biggest interest in “green driving behavior”, then the introduction of a multichannel advice system might help in order to convince drivers of the importance of ecological driving. However, this aspect needs to be investigated in further research. On the other hand it cannot be neglected that the majority of the participants preferred the visual system because it was less disturbing, even though they felt more distracted using this modality compared to the haptic modality. Therefore when designing haptic advices it is important to consider that they do not make the drivers feel patronized. Especially since the haptic modality is of advantage in terms of reducing distraction, it seems valuable to further pursue and improve the suitability of haptic advices for eco-driving. Meanwhile before entering the market, there is also a need for studying the impact of the prioritization of different ecological and non-ecological advices. Within the eCoMove project the next step will be the detailed specification and implementation of the fine-tuned HMI concepts into the eCoMove demonstrator. Additional research findings will be derived from the planned user validation in the final project phase.

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