2017 IEEE World Haptics Conference (WHC)
Fürstenfeldbruck (Munich), Germany
6–9 June 2017

An Evaluation of the Influence of Haptic Feedback on Gaze Behavior during In-Car Interaction with Touch Screens

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***Abstract*— A major motivation for the introduction of haptic feedback in in-vehicle touch screens is the reduction of the eyes-off-road time. This paper presents a study which compares different feedback conditions for touch screen interaction: (1) visual feedback, (2) combined visual-haptic feedback, and (3) haptic feedback only. Subjects had to select target buttons on a touch screen during simulated driving. Our results show that haptic feedback significantly reduces the eyes-off-road time and the subjectively perceived workload. When visual content is available, gazes on the touch screen are more frequent than necessary. And even in the absence of visual content, complete eyes-free interaction was only occasionally spotted, and subjects still looked at the screen initially. We assume that this is due to the necessity of an initial reference position.**

I. Introduction

Touch screens and touch-sensitive surfaces are commonplace in modern automotive dashboards and more and more replace mechanical inputs (e.g. [1], [2]). Several factors contribute to this trend, e.g. the design flexibility that is offered by displays or their ability to handle multiple functions [3].

While mechanical inputs like buttons or slider provide users with orientation, guidance and tactile feedback [4], these cues are missing on flat touch surfaces. As a matter of fact, more visual attention must be directed on the touch screen, increasing the eyes-off-road time. The implications on driving safety and the risk of traffic accidents are summarized in [5]. This motivates recent research and development activities to enrich touch screens with synthetically generated haptic feedback.

In this paper, we report findings of a user study that investigated the effect of haptic feedback on task performance and gaze behavior during simulated car driving. In particular, the scope of the study was led by two major questions: (1) are subjects able to operate a touch screen eyes-free with haptic feedback, and (2) are subjects willing to rely on haptic feedback if visual feedback is also available.

II. Background

We present a simplified model of user touch screen interaction with virtual push buttons in [6]. This model describes different interaction states of a human finger moving over a touch screen to find and activate a desired virtual push button. These interaction states can be enhanced with haptic feedback. According to Kim and Lee [7], most previous studies focus on providing haptic feedback at the state transition of pushing down a virtual button, which is referred to as click feedback (e.g. [8], [9]). Haptic feedback can also be provided during the process of pushing down a button [7]. This type of feedback mimics the force-displacement curve of a mechanical button to further enhance the perceived realism of a virtual button. Pakkanen et al. (2010) introduce haptic feedback when the finger moves over a button edge, referred to as edge feedback [10]. Further differentiations between upwards (i.e. moving the finger from the non-interactive background on to the button) and downwards movements are possible. An on-button haptic feedback (e.g. continuous vibration) can be provided when the user moves his finger on a button (i.e. moving the finger on a single button without crossing the button edges). This enables users to differentiate between a button and the non-interactive background, where it is recommended to have no synthetic haptic feedback in the latter case [11]. Finally, different haptic textures can be provided on different buttons, as was presented in the Bosch CES 2016 haptic feedback touch screen demonstrator, enabling users to identify buttons.

A number of studies have been performed to assess the effect of haptic feedback on touch screen interaction and driving performance in an automotive context. Lee and Spence (2008) examined the effect of multimodal feedback provided by a touch screen on drivers' performance in a perceptually demanding dual-task situation [12]. They report positive effects of multimodal feedback over unimodal visual feedback in both secondary task completion time (mobile phone entry task) and reaction time towards an approaching car in the driving simulation. Richter et al. (2010) performed a preliminary qualitative study with 5 subjects to investigate the effects of tactile feedback on drivers' visual attention, driving performance (lane change task, LCT) and secondary task performance on a haptic touch screen [13]. Only trends can be reported due to the small number of participants, indicating that haptic feedback reduces the number of misplaced activations, and increases the usability of small GUI elements. Pitts et al. (2012) conducted a user study to evaluate the effect of different types of uni-, bi- or trimodal touch screen feedback on driving and secondary task performance, affective response, and subjective workload [5]. While the mean lane deviation increased significantly relative to a baseline when the touch screen task was introduced, none of the feedback types was able to reduce lane deviation significantly in comparison to the unimodal visual feedback condition. Note that gaze behavior was not examined in [5], [12] and [13].

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978-1-5090-1425-5/17/$31.00 ©2017 IEEE

While the previously described studies utilize haptic feedback on touch screens, several studies also demonstrated positive effects of haptic feedback on touch pad interaction These studies are somewhat different from the research scope of the present paper, concerning mounting position of the haptic input device and type of interaction (direct vs. indirect) but still provide relevant input for the present study. Domhardt et al. (2013) evaluate the effect of haptic feedback on driving performance and gaze behavior during touch pad interaction [14]. While subjects completed the LCT, they performed secondary tasks that are typical for car driving (e.g. climate control). There were no significant differences in driving performance with haptic feedback. However, both gaze diversion from the road and secondary task completion time improved significantly when haptic feedback was provided. Mullenbach et al. (2013) used a TPaD variable friction touch pad (see also [16], [17]) to provide haptic feedback in a touch pad targeting task and a slider adjustment task [15]. Subjects performed these tasks while driving on a four-lane simulated road at 40 mph with 2-4 s headway to a vehicle ahead. As a results, the eyes-off-road time reduced significantly with haptic feedback. However, the targeting task performance was significantly worse in the haptic feedback condition, indicating that the haptic feedback provided with the TPaD tablet did not enable precise targeting. Subjects preferred combined visual-haptic feedback significantly, which was both less mentally and less visually demanding. A different type of haptic feedback was utilized in the study described in [18]. The touch pad was based on an array of 1200 Pins on an area of 10 x 7.5 cm, where each pin could be lifted up to 0.8 mm. During the main task (driving, not further specified), subjects performed menu tasks with the navigation system (not further specified). As a result, the haptic touch pad outperformed all other conditions (e.g. flat touch pad with and w/o visual feedback) regarding driving performance, secondary task performance, and gaze behavior. Visual feedback in a separate display (Head Unit) worked like an eye catcher, causing additional visual distraction during driving.

a) b)

Figure 1. a) experimental environment b) example image of the camera facing the subject

In the study described in this paper, we evaluate the effect of haptic feedback during touch screen interaction. As there was no visual content on the screen in one experimental condition, the results can also be transferred to touch pad interaction. While a click feedback gives a perceivable confirmation only when an already identified button is activated, edge and on-button feedback can also support in finding a button without looking at the screen. Therefore, we utilized both click and edge feedback in our study, while on-button feedback was not implemented.

III. Methods

A. Participants

Thirty subjects (9 female, mean age 31 years, age range 21 to 56 years) with normal or corrected to normal vision and hearing participated in the study. Five of the participants were left-handed by self-report. All subjects gave their written informed consent prior to participation. In total, the study took approximately 1 hour to complete.

B. Apparatus and Stimuli

The test apparatus resembled an automotive touch screen in a typical size and appearance. A Raspberry Pi 2, Model B was used to control the Raspberry Pi 7” capacitive touch screen (screen dimensions: 194mm * 110mm * 20mm, weight: 277g). We used an electrodynamic exciter (Visaton EX 45 S) for haptic actuation, which was glued under the touch screen after removal of the touch screen driver board. An amplifier (Visaton AMP 2.2) was used to adjust the haptic feedback strength. Force sensing resistors (FSR-402, Interlink Electronics) were placed under each corner of the touch screen to measure the applied pressure. The secondary task was written in Python and implemented on the Raspberry Pi, which evaluated the input signals from the touch screen and the force sensing resistors, and triggered the haptic feedback.

A 30” screen and a Logitech steering wheel were used to display and interact with the driving scene. The touch screen was placed at the right-hand side of the steering wheel and mounted on a wooden frame at an angle of approximately 40° (see Fig. 1). Two cameras were used to monitor the subjects, one placed on top of the screen recording the drivers’ gaze behavior, and one mounted on a tripod facing the touch screen (not visible in Fig. 1). A loud speaker was connected to the Raspberry Pi to provide the commands in the secondary task.

Click and edge feedback signals were implemented based on the findings of previous studies (see [6]). The edge feedback signal was a pulse of 150 Hz sinusoidal vibration with a duration of approx. 15 ms and 80% amplitude of the click signal. The click signal was implemented as a double pulse (two pulses of sinusoidal vibration at 150 Hz with a duration on approx. 15 ms, with 10 ms pause in between). While this click signal does not mimic the haptic feedback of a mechanical button, it can be clearly differentiated from the edge signal. We did not perform acceleration measurements, and optimized the signal strength towards subjective preference. The click signal was triggered upon activation of

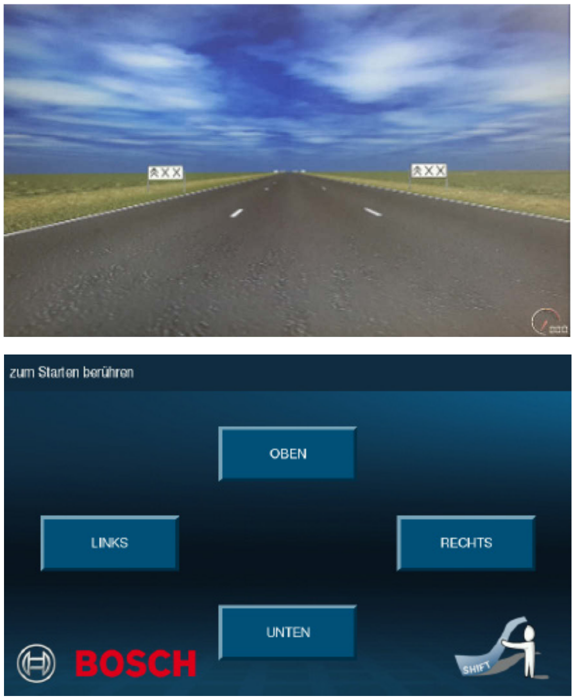
a)
b)


Figure 2. a) screen shot from the lane change task, b) button layout in the touch screen task

a button, which was detected whenever the pressure applied on a button exceeded a certain limit that was determined in pre-tests. The edge signal was triggered whenever the finger moved from the non-interactive background on a button and vice-versa. No differentiation between upward and downward edges was made. The edge signal was also triggered when the initial contact of the finger was on a virtual button, while no haptic feedback was generated when the initial contact of the finger was on the background.

C. *Procedure*

In the driving task, participants performed the lane change task (LCT, see Fig. 2a), a standardized lab based method to quantify driving performance degradation caused by a secondary task (ISO 260222, 2010). In the LCT, subjects drive at a constant speed of 60 km/h on a straight, three-lane road. No other cars are present on the road at all time. Subjects are instructed to change lanes as fast and accurate as possible as soon as a sign on each side of the road indicates to do so. The target lane information appears 40 meters ahead of the signs. An LCT track takes three minutes to complete and requires 18 lane changes.

In the secondary task, participants had to press one out of four buttons located at the left, right, top and bottom side of the graphical user interface (see Fig. 2b). The target button was announced with a recorded spoken command via the loud speaker. Subjects were asked to select the button within 7 seconds after the initial announcement, and move their hand back to the steering wheel afterwards. Multiple corrections were possible within these 7 seconds. The response time was not measured. The next target button was announced after a random interval ranging between 8 and 10 seconds after the previous target button announcement, irrespective of whether the correct or the wrong button was selected by the subject. One trial consisted of 21 randomized button press tasks, where each button location was defined as target at least 5 times. The secondary task was started manually by the experimenter at a specific visual landmark in den driving task to ensure that both tasks were roughly synchronized.

D. *Experimental Design*

According to the ISO standard, participants performed the LCT without secondary tasks repeatedly in order to familiarize, until their mean lane deviation fell below a threshold of 1m. They were then instructed to the secondary task, followed by the recording of the baseline driving task, i.e. LCT without a secondary task. After that, subjects performed three experimental trials with LCT and secondary task, with type of feedback as a within-subject factor: Visual only (V) where the buttons were visible but no haptic feedback was triggered, Visual + Haptic (V+H) with visible buttons and haptic feedback, and Haptic only (H), where the buttons could only be felt but were not displayed. The trials were performed in randomized order. A second baseline was recorded after the experimental trials.

The dependent variables were driving performance, secondary task performance, and gaze behavior. Furthermore, the subjective workload was assessed with questionnaires after each experimental trial. For the driving performance, the mean deviation from a normative path is derived as a single measure. The perception and reaction to lane-change signs shows the drivers' awareness of the driving environment, and the lane-keeping performance reflects the drivers' ability to control the vehicle. Late or missed perception of signs, slow lane change, and poor lane-keeping thus results in greater deviation from the normative path ([19], [20]). An analysis software provided with the LCT was used to compute this measure.

For secondary task performance, the mean target accuracy (%) was derived with an analysis script. This script recorded the target button along with the button that was actually pressed by the subjects. It has to mentioned, that, especially in feedback condition H, the number of correctly pressed buttons reported from the analysis script was smaller than the number presented here. A re-evaluation of the recorded videos showed that subjects in deed pressed the correct button in almost all cases, but with a pressure that did not exceed the activation threshold. As this does not reflect the subjects' worse secondary task performance but rather a suboptimal threshold design, these cases were re-labeled as correct presses. The activation threshold was adapted after the study. For gaze behavior, we evaluated the glance count (i.e. number of glances) and total glance duration towards the touch screen (total amount of time spent for eye gaze on the touch screen, in ms). These measures were manually derived from the recorded videos by the main experimenter, and verified from a second person on a random base. The experimental hypotheses were:

- H1: Eyes-free touch screen interaction is possible with haptic feedback
- H2: When haptic feedback is added to visual feedback, driver distraction is reduced, compared to when only visual feedback is provided.

H3: When both visual and haptic feedback are available, subjects rely less on the haptic channel, compared to the when only haptic feedback is provided.

H4: When subjects experience the haptic feedback condition first, they are more willing to rely on the haptic channel in the combined visual-haptic condition.

IV. Results

A. Secondary task performance

The mean accuracy in the secondary task for each feedback condition is shown in Fig. 3 together with 95% t-confidence intervals. In the feedback conditions V and V+H, no mistakes were made at all, leading to a 100% target accuracy. In feedback condition H, two subjects made 1 and 2 mistakes, respectively, leading to a slightly worse secondary task performance in condition H by tendency. A Friedman test showed no significant differences in the secondary task performance ($p>0.05$)

B. Driving performance

The mean path deviation in the LCT for each feedback condition is shown in Fig. 4. In all feedback conditions, the mean path deviation is below 0.5 m. The mean path deviation is least in feedback condition V+H (0.44 m) and largest in feedback condition H (0.48 m) by tendency. A Friedman test revealed no significant differences in mean path deviation ($p>0.05$).

C. Gaze behavior

The gaze behavior is described with two measures: the mean number of glances on the touch screen and the total glance duration on the touch screen. The mean total number of glances for each feedback condition is displayed in Fig. 5. It is lowest in feedback condition H (21.4) and largest in feedback condition V (31.3). A Friedman test showed significant differences (at level 5%), and post-hoc tests were performed. Wilcoxon signed-rank tests revealed statistically significant differences between V and H ($p<0.001$), between V and V+H ($p<0.001$), and between V+H and H ($p<0.05$). The total duration of glances on the touch screen for each feedback condition is shown in Fig. 6. The total glance duration towards the touch screen is highest in feedback condition V (12191 ms) and lowest in feedback condition H (4809 ms). A Friedman tests showed significant differences and post-hoc tests were performed. Wilcoxon signed-tank tests revealed statistically significant differences between V and H ($p<0.001$), between V and V+H ($p<0.001$) and between V+H and H ($p<0.001$).

It was furthermore evaluated whether the order of feedback condition has an effect on the gaze behavior in condition V+H. Subjects were divided into two sub-groups, one that perceived feedback condition V+H before H, and one that perceived V+H after H, and glance count as well as total glance duration were evaluated for both subgroups (see Fig. 7). Each subgroup consisted of 15 subjects. The total glance duration on the touch screen in feedback condition V+H was 7399 ms when subjects performed the secondary task with

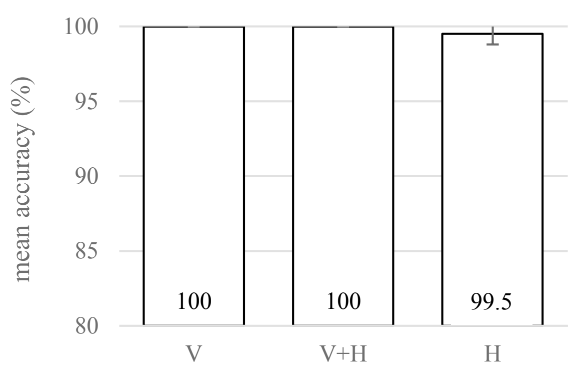


Figure 3. Mean target accuracy (%) for each feedback condition. Error bars denote CI (95%)

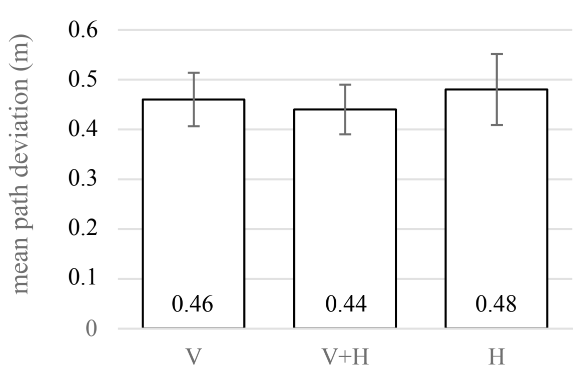


Figure 4. Mean path deviation (m) for each feedback condition. Error bars denote CI (95%)

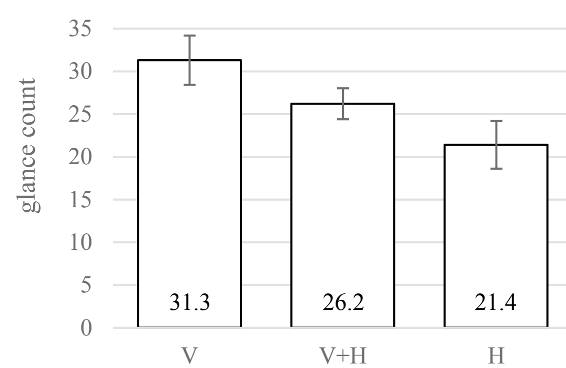


Figure 5. Number of gazes on the touch screen for each feedback condition. Error bars denote CI (95%)

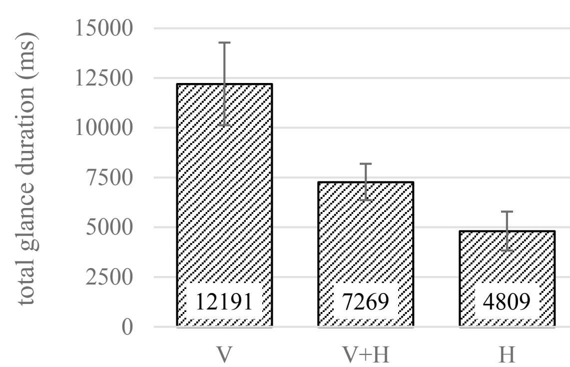


Figure 6. Total amount of time spent for eye-gazes on the touch screen for each feedback condition. Error bars denote CI (95%)

only haptic feedback before, and 7139 ms when the order of feedback conditions was opposite. The glance count values in feedback condition V+H were almost equal with 26.1 when H was perceived before V+H and 26.4 when H was perceived after V+H. Two sample t-tests revealed no significant differences in both numbers of glances and total glance duration (p>0.05) in condition V+H.

D. *Mental effort*

The perceived mental effort for each feedback condition as stated by the subjects is shown in Fig. 8. The perceived mental effort is lowest in the combined visual-haptic feedback condition (62.9) and highest in the haptic-only feedback condition (82.2). A Friedman test showed significant differences (p<0.05) between the input conditions. Wilcoxon signed-rank tests revealed that the differences are statistically significant between V and V+H (p<0.001), and between H and V+H (p<0.001), while the differences between V and H are not significant (p>0.05).

It is finally stressed that, in each case, the statistically significant results remained valid after a Bonferroni-adjustment for the post-hoc tests.

V. Discussion and Conclusion

Hypothesis H1 is fully supported. The results for mean target accuracy show that eyes-free touch screen operation is possible, at least for comparably simple tasks as in the present study. Even without any visual representation on the screen, subjects found and selected the correct target button with almost perfect accuracy.

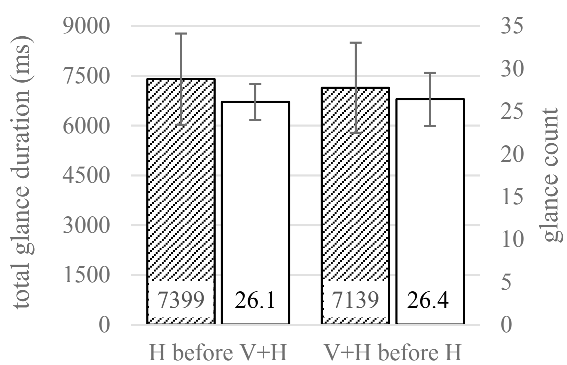


Figure 7. Glance count and total glance duration in condition V+H for different orders of feedback condition. Error bars denote CI (95%)

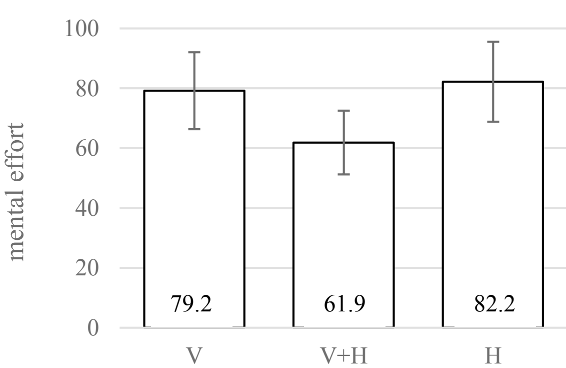


Figure 8. Perceived mental effort (self-assessment) for each feedback condition. Error bars denote CI (95%)

As the LCT is especially sensitive to cognitive workload, the results for LCT driving performance indicate that no change in cognitive distraction can be measured. Therefore, hypothesis H2, which states that driver distraction is reduced with haptic feedback, cannot be supported for cognitive distraction. While the mean path deviation is slightly reduced by tendency with additional haptic feedback, an increase by tendency in the haptic-only feedback condition can be observed, indicating a slightly higher cognitive demand when only haptic feedback is provided. For visual distraction, however, hypothesis H2 is fully supported. The number of glances on the touch screen can be reduced by 16% with additional haptic feedback compared to the visual feedback condition, and by almost 32% when only haptic feedback is provided, again with feedback condition V as baseline. The total glance duration on the touch screen is reduced by 40% with visual and haptic feedback, and by 60% with only haptic feedback compared to the visual feedback condition. However, even in the absence of visual content, which is the case in the haptic feedback only condition, subjects still look on the touch screen, and complete eyes-free interaction is only occasionally spotted.

A re-evaluation of the recorded videos on a random base indicates that most of the glances on the touch screen in the haptic feedback condition occur in the initial stage when subjects move their hand from the steering wheel towards the touch screen. These initial glances might be necessary to roughly position the finger on the screen, while fine adjustments of the finger position can be done with the haptic cues.

With regard to the gaze behavior in the combined visual-haptic feedback condition, it can be seen that subjects took their eyes off the road more often than necessary, as is obvious given the statistically significant differences in the gaze behavior in the haptic feedback only condition. Even though they can accomplish the secondary task with less gaze attention, subjects still rely on visual feedback. Therefore, hypothesis H3 is supported.

Hypothesis H4 is rejected, however. The gaze behavior in the combined visual-haptic feedback condition does not differ significantly when the haptic-only feedback condition was experienced before or afterwards. Subjects that performed the secondary task successfully with haptic-only feedback before they performed the secondary task with both visual and haptic feedback did not rely less on the visual channel in the V+H feedback condition than subjects that performed the secondary task with opposite order of feedback conditions. Even though these subjects already experienced that the secondary task can be completed with less visual attention towards the touch screen, they were not willing to reduce the off-the-road gazes to the same extent.

Our results show the benefit of additional haptic feedback on touch screen interaction, at least for comparably simple tasks as in the previous study. This is especially evident regarding the gaze behavior and the subjectively perceived mental effort in the touch screen task. Furthermore, a slightly improved driving performance by tendency can be observed when additional haptic feedback is provided. Effects on the touch screen task performance could not be observed, as the task itself was intentionally very simple. Our results further show that – even though complete eyes-free touch screen interaction was occasionally spotted in individual tasks – most drivers still initially look at the touch screen. We assume that these initial glances are necessary to reach a certain reference position with the finger, while further finger movements to fine adjust the finger position can be done with haptic cues. In contrast to our lab environment, most real automotive dashboards still contain graspable elements (e.g. perceivable edges of an embedded touch screen), which serve as reference points and might further reduce these initial glances. It is our plan to investigate this with further studies in the future.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 Research and Innovation Program under grant agreement No 645145.

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