Enhancing Touch Control on the Steering Wheel with Force Input

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Abstract: *Steering wheel controls have become an essential interface for interacting with in-car human machine interfaces. The increase in both number and complexity of features in the car challenges the scalability of button-based mechanical steering wheel interfaces. Alternatives such as touch input are making their way into steering wheels of mass production cars. Multi-level force input adds a degree of freedom for touch interaction and therefore increases the richness and expressiveness of touch interfaces. We propose to implement force input into steering wheels by using force sensitive touchpads. We explored multi-level force input on the steering wheel in an extensive controlled experiment. The results provide insights into the user sensory threshold in discriminating differences in force input on a steering wheel and its impact on design specifications for force sensing touchpads.*

Keywords: Touch; Force; Touchpad; Forcepad; Steering wheel; Force threshold; Experiment; Force discrimination;

Introduction

Over the past decade, the steering wheel has become an essential interface due to its accessible location and multi-functional controls. It enables interaction with in-car Human-Machine Interfaces (HMIs) such as instrument clusters and head-up displays (HUDs). Currently, steering wheel interfaces leverage mechanical controllers such as buttons and scroll wheels, with each controller being mapped to a particular feature. This mapping leads to two pertinent shortcomings: (a) the increase in the number and complexity of features challenges the scalability of the interface and (b), as a result, users have to deal with increased cognitive load, complex spatial mappings, and difficult learning curves.

Researchers and manufacturers have investigated alternative input methods on the steering wheel. For example, Diwischek et al. [3] introduced virtual switches on the steering wheel. Döring et al. [4] addressed multi-touch interaction in the center of the wheel. Similarly, touch on the wheel rim has also been investigated by Koyama et al. [7]. Most recently, one OEM has introduced optical finger navigation technology replacing buttons on the steering wheel. All of these approaches leverage directional gestures or common multi-touch gestures on 2D surfaces like touchscreens and touchpads.

Adoption of multi-level force input during touch interaction is increasing in mobile devices (smartphones, smartwatches, and notebooks) as a way to increase the richness and expressiveness of touch interaction. We propose implement force input into steering wheel interfaces by using force sensitive touchpads. We developed a concept steering wheel with two force sensing touchpads—one for each thumb. Specifically, we investigate the user sensory threshold in discriminating differences in force input in an extensive controlled experiment. Based on the results, we identify force threshold differences for multi-level force input and develop tolerance recommendations for force sensing on touchpads in the steering wheel.

Related Work

There is a growing body of research on interaction on and around the steering wheel. As our work is at the intersection of input on the steering wheel and in-car touch and force interfaces, we discuss related work along three main avenues: touch input and gestural input on the steering wheel and force input in the car.

Touch and Gestural Input on the Steering Wheel: Döring et al. [4] implemented a multi-touch enabled steering wheel and studied gestural input. They transformed the center of the steering wheel into an interactive touch surface for in-vehicle functions such as infotainment control, etc. They contributed an interaction language and evaluated the prototypical setup in a driving simulator. They showed that visual demand is significantly reduced through multi-touch interaction on the steering wheel.

Touch interaction for list navigation was investigated by González et al. [5]. They placed small Synaptics Touchpads around the steering wheel and compared different list selection techniques, e.g. by inputting leading characters to jump to respective sections in the list. Werner [15] provides an overview of touch-related projects on steering wheel interactions. He also contributes interface concepts for bimanual interaction on the steering wheel. The main contribution is a hybrid interaction approach where one half of the steering wheel is touch-enabled and the other half uses physical buttons to allow for mode switches.

Gestures on the steering wheel were investigated by Mahr et al. [9]. They mapped common gestures for zooming, swiping and circling to comfort functions and refined these gestures together with participants in a study. Their main insight was a recommendation to place interactive hotspots for gesture interaction closer to the steering wheel. The interaction space for gestures on the steering wheel was also explored in [1]. Multimodal interaction with the steering wheel was investigated by Pfleging et al. [12]. Inspired by Döring et al. [4], they transformed the center of the steering wheel into an interactive surface and added a microphone to capture spoken language. They implemented a 2-step process. Users first have to utter an object they want to control (e.g. “passenger window”). The recognized object can then be controlled using gestures on the steering wheel.

Other related studies include infotainment control using on-wheel gestures [8], wheel-based interaction leveraging electromyography to detect abduction, squeeze, extension and flex grip interactions [2] and also wheel-based interaction using optical sensors [7]. Meschtscherjakov et al. [11] explored the back of the steering wheel for text input in combination with a HUD display. Touch based input of hand-written text was also explored by Kern et al. [6] on the steering wheel and the central console.

Force Input in the Car: Richter et al. [13] implemented a force-sensing touchscreen using force sensitive resistors (FSRs) to support three force levels. Specifically, they used force to enable a push-to-select interaction and a higher force levels for additional degrees of freedom. The force is also mapped to different tactile feedback using linear actuators. They evaluated their system using a number pad scenario where participants had to key in number sequences. When compared to an ordinary touch surface, their implementation showed fewer errors for user interfaces with small targets and only a little difference for larger targets.

Sheik-Nainar et al. [14] contribute a comparative study of interface concepts for target selection using a force-enabled touchpad in the central console. They found that an absolute mapping of the touchpad input space to the display space yields a more effective and efficient user interaction than a relative input mapping. They also found that participants had significantly reduced eyes-off-the-road time.

Diwischek and Lisseman [3] investigated haptic feedback for force-enabled virtual steering wheel buttons. Their main contribution is a comparison of different haptic stimuli to identify an “optimal” tactile feedback for virtual button switches in terms of user preference

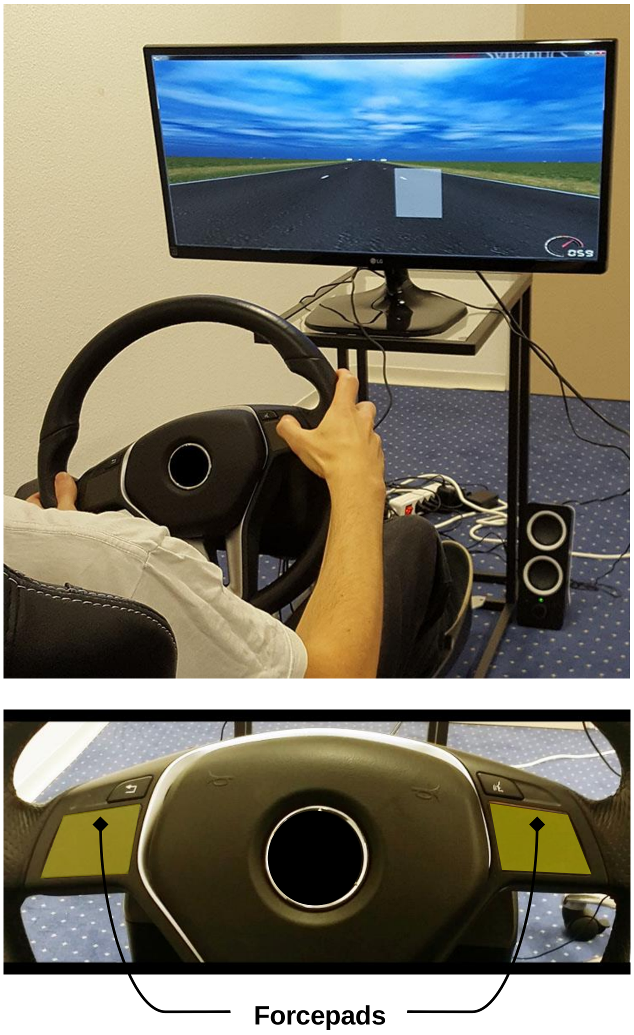

Figure 1. Driving simulator setup (top) and close-up of the steering wheel prototype (bottom)

Controlled Experiment

We conducted a controlled experiment to investigate the user sensory threshold in discriminating differences in force input. Furthermore, we address two additional research questions: what are appropriate force threshold differences for multi-level force input and how do these translate to tolerances for force sensing in touchpads?

Apparatus: The experiment was conducted using a driving setup, running Mattes’ Lance Change Task simulator software [10]. The setup was comprised of the prototype steering wheel with force-sensing touchpads (Synaptics ForcePad$^{\text{TM}}$) (see Figure 1 top). The forcepads had a force report range of up to 8N. The rest of the setup includes a driving seat and a 27” ultra-wide display (see Figure 1 bottom).

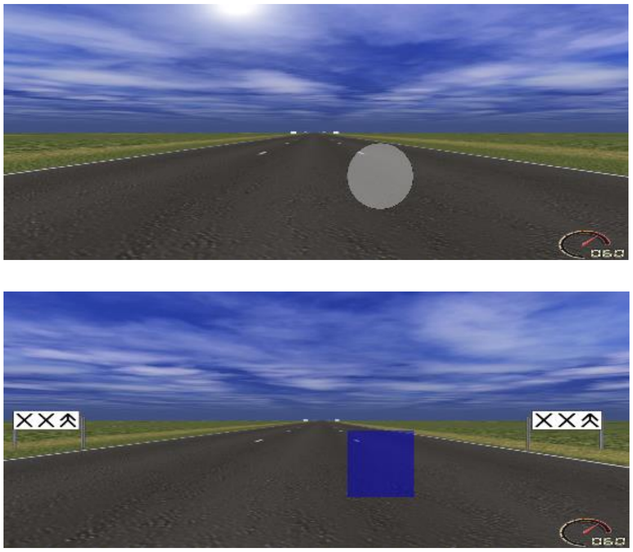

Figure 2. The top part shows the first prompt of a button pair, visualized as a grey circle. The lower image shows a situation where a participant activated a rectangular button, hence the blue color.

Experiment Design and Method: The primary task was to drive in the driving simulator. Following the lane change task methodology, participants drove on a three lane course of which two lanes were closed. Virtual signs prompted participants to drive into the open lane, i.e. participants had to change lanes frequently (see Figure 2 bottom).

To address our research questions, we chose a force level discrimination task as the secondary task. The task was presented as a two-alternative forced choice method. Participants were presented pairs of stimuli and they had to rate whether the stimuli could be activated using similar or different forces on the forcepad. Varying the force difference between the stimuli allowed us to estimate the "just noticeable difference" in terms of force activation.

Table 1. Overview of utilized nominal forces and applied differences in percent. Each cell shows the pair of force threshold participants compared per trial.

		Nominal Forces [g]			
		100	200	300	500
Percent Difference	0%	100 / 100	200 / 200	300 / 300	500 / 500
	10%	95 / 105	190 / 210	285 / 315	475 / 525
	20%	90 / 110	180 / 220	270 / 330	450 / 550
	30%	85 / 115	170 / 230	255 / 345	425 / 575
	50%	75 / 125	150 / 250	225 / 375	375 / 625
	70%	65 / 135	130 / 270	195 / 405	325 / 675

The latter can be used to derive respective force thresholds as well as sensor accuracy requirements. It will also provide answers to the amount of force levels a user is able to discriminate.

The secondary task was implemented as follows: participants were prompted with buttons that appeared on the display, similar to a simulated HUD. A series of two consecutive buttons was displayed. The general objective was to activate each button by applying force on the forcepad. Targets presented where initially gray. Upon applying force equal to or above the preset threshold, the color changed to blue and an audio feedback was provided. First a circular button was displayed, then a rectangular button (see Figure 2). Eventually, the participant was prompted to rate whether the applied force felt similar or different per button pair, simply by reporting to the experimenter. Depending on where the button pair was displayed (i.e. in the left or right half of the display), the corresponding forcepad had to be used for activation. The entire forcepad was mapped to the button.

The force thresholds for each button pair were computed based on a nominal force (in grams) adjusted by a difference factor (in percentage) (see Table 1). For instance, a nominal force of 500g with 70% difference applied, leads to an absolute force difference of 350g and a button pair of 325g and 675g respectively (500g ± 175g).

In sum, the independent variables were

- Nominal force (100g, 200g, 300g and 500g)
- Difference (0%, 10%, 20%, 30%, 50% and 70%)
- Forcepad location (left and right)

The dependent variable was the similarity rating. The order was counter-balanced; each button pair was repeated twice with order balancing (e.g. the first button pair responded to 325g/675g, the second to 675g/325g or vice versa).

The study was conducted with 16 participants in a single user session. There were seven female and nine male participants, one participant was left handed and the average age of participants was 37 years. Each session lasted about 30 minutes. Participants were given ample time to test drive the simulator, as well as to try both the primary and secondary tasks. They were asked to interact with their thumbs and maintain a steering wheel grip at 9 o'clock and 3 o'clock. The study commenced once the participants felt comfortable with the task. In total, 1536 trials (4 nominal forces * 6 percent differences * 2 forcepad locations * 2 repetitions * 16 participants) were recorded. Pauses between trials, i.e. button pairs, were randomized between 2 and 5 seconds.

Table 2. Average similarity ratings across all participants. Colors provide a highlight of participant ability to discriminate a specific force threshold combination.

Nominal Force [g]

Percent Difference	100	200	300	500
0%	**78.13%**	**71.88%**	**59.38%**	**56.25%**
10%	81.25%	62.50%	71.88%	53.13%
20%	68.75%	71.88%	56.25%	46.88%
30%	71.88%	56.25%	53.13%	65.63%
50%	59.38%	71.88%	59.38%	59.38%
70%	78.13%	59.38%	65.63%	40.63%

Left Forcepad

Nominal Force [g]

Percent Difference	100	200	300	500
0%	**87.50%**	**71.88%**	**56.25%**	**59.38%**
10%	84.38%	62.50%	75.00%	59.38%
20%	78.13%	81.25%	71.88%	59.38%
30%	68.75%	53.13%	65.63%	50.00%
50%	84.38%	65.63%	46.88%	46.88%
70%	71.88%	71.88%	56.25%	37.50%

Right Forcepad

Results and Discussion

Table 2 shows the average similarity ratings across all participants for each forcepad, i.e. the percentage of participants who rated stimuli as "similar". A summary for both forcepads is shown in Table 3. The similarity ratings were between 82.81% and 57.81% for two identical stimuli (i.e. 0% difference) and between 82.81% and 39.06% for non-identical stimuli. Typically, the point of subjective equality (PSE) is considered at 50% and a similarity rating of 25% (i.e. a detection rate of 75%) is used as a threshold to consider two stimuli different. The colors in tables 2 and 3 are mapped to this scale: green indicates ratings up to PSE, red indicates undetectable differences and orange is mapped to ratings in-between.

The analysis yielded significant main effects for both nominal forces and percent differences. All differences between nominal forces were statistically significant ($p < .05$), except between 200g and 300g. Differences between 10% and 70% were significant ($p <.05$). All other differences were not significant. No significant main effects were observed for the forcepad location. Also, no significant interaction effects were observed. Furthermore, a high correlation between correct answers and time was found ($r = .90$). In the following, we discuss the results in detail.

Table 3. Average similarity ratings across all participants and both forcepads.

Nominal Force [g]

Percent Difference	100	200	300	500
0%	**82.81%**	**71.88%**	**57.81%**	**57.81%**
10%	82.81%	62.50%	73.44%	56.25%
20%	73.44%	76.56%	64.06%	53.13%
30%	70.31%	54.69%	59.38%	57.81%
50%	71.88%	68.75%	53.13%	53.13%
70%	75.00%	65.63%	60.94%	39.06%
Mean	74.69%	65.63%	62.19%	51.88%

Similary Ratings: In general, we found two main themes. First, the higher the nominal force, the *less likely* a user perceives two *identical* stimuli (i.e. 0% difference) as similar. A second theme emerges when considering the mean similarity ratings for non-identical stimuli across nominal forces: the higher the nominal force, the more likely a user perceives two *non-identical* stimuli (i.e. percent difference > 0%) as different.

Looking at the similarity ratings more closely, the data shows that it was particularly hard for participants to identify similar stimuli for nominal forces of 300g and 500g. Also, different stimuli with a nominal force between 100g and 300g were hard to detect.

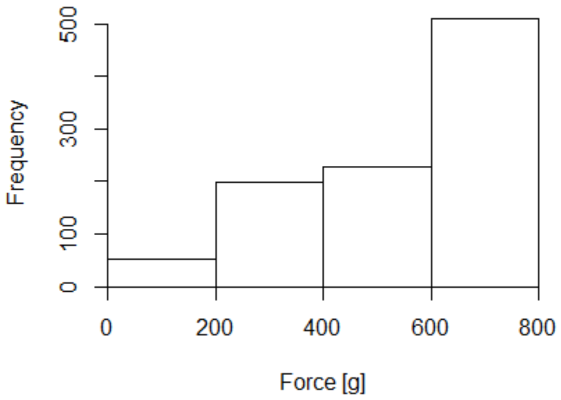

Figure 3. Histogram of applied forces in grams throughout the entire experiment.

We hypothesize that this is due to a strong base force that participants applied. Figure 3 shows the distribution of the applied forces throughout the experiment and their frequencies. The histogram indicates that only few trials were performed with forces smaller than 200g. We further hypothesize that the grip that users applied to the steering wheel affords applying stronger forces with one's thumb.

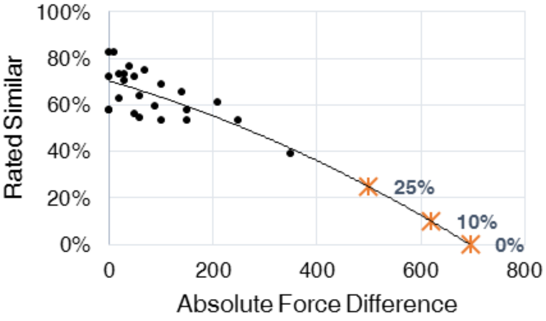

Figure 4. Average similarity ratings plotted against absolute force difference in Grams. Line indicates fit of a 2^{nd} order polynomial model ($R^2 = 0.44$).

Force Levels and Thresholds: The analysis of the average similarity ratings indicates that distinguishing multiple force levels on the steering wheel is a challenging task. Specifically, a mapping of multiple functions to forces below 200g seems unusable. Figure 4 illustrates the average similarity ratings according to the absolute force differences (i.e. 500g nominal force with 70% difference yields an absolute difference of 350g). The prediction of our model indicates that at an absolute force difference of 525g, 25% of the stimuli would be rated as similar, at a difference of 620g, 10% of the stimuli would be rated as similar and, last, at a difference of 695g, our model yields an average similarity rating of 0%. Thus, we hypothesize that a maximum of two force levels seems appropriate for force-based touchpad interaction on the steering wheel. For example, in addition to a tap. These interactions could be defined with an absolute force difference of 525g with *press* at 100g and *press hard* at 625g. Tap can be disambiguated based on the temporal touch data.

Accuracy requirements: A high sensor accuracy is typically preferred from an engineering point of view. However, even at a difference of 0%, the users perceived differences between the virtual target activation forces. This might be due to the nature of the thumb interaction while gripping the steering wheel, as well as the added cognitive load of the driving task. As a consequence, the tolerance requirement can be relaxed without affecting the effectiveness of force interaction. Table 3 indicates that an accuracy of 30% might be a potential candidate. With nominal forces of 200g and above, participants were able to discriminate two stimuli about half the time. Depending on the application, the accuracy can even be further relaxed: e.g. when a continuous mapping of force to functionality is not required by the user interface implementation and therefore only specific thresholds need to be defined.

Conclusion and Outlook

In this paper, we explored multi-level force input on the steering wheel. We contributed results from an extensive controlled experiment with 16 participants that explores the user sensory threshold in discriminating force differences. Based on our results, we developed tolerance recommendations for force sensing accuracy and identified force threshold differences for multi-level force input on the steering wheel.

Two main conclusions can be drawn from the study. First, a maximum of two force levels for discrete actions (e.g. direct finger selection of items). Activation thresholds should be based on absolute force differences in-between. Based on our results, a force difference of at least 525g should be considered for steering wheel interfaces. Second, as both the user sensory threshold in discriminating force differences and the applied base force turned out to be rather high, the tolerance requirement can be relaxed. We propose an accuracy of 30% for steering wheel interfaces based on force-enabled touchpads.

Future work will focus on comparing force input in different areas of the car, e.g. steering wheel, central information display and the horizontal area of the center console, commonly used for touchpad implementation. We hypothesize that the input location will have a great impact on the user sensory threshold, as well as the applied forces.

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