Where's My Button? Evaluating the User Experience of Surface Haptics in Featureless Automotive User Interfaces

Stefan Josef Breitschaft, Alexander Pastukhov, and Claus-Christian Carbon

***Abstract*—Advancements in user interface technologies and demands of design engineering led to increasing implementation of large and mostly flat interactive surfaces in automotive. Recent discussions in the context of in-vehicle usage of touchscreens advocate for the use of haptic feedback to restore the explore- and feel-qualities typically experienced in traditional physical button interfaces that contribute to intuitive, eyes-free, and tactually rich interactions. Haptic technologies that include a friction modulation approach seem especially promising to convey a high-quality feeling. This research reports an experience-oriented evaluation of an electrostatic friction haptic display in an in-vehicle direct touch interaction context. The evaluation was based on an automotive multitask setting (primary driving-task and secondary target-selection-task) with a 2 × 2 feedback modality design (factors haptic/audio with levels absent/present). The objective variables (response time, errors, and performance on the primary task) did not differ between feedback modalities. Any additional feedback to a visual baseline enhanced the user experience, with the multimodal feedback being preferred by most participants. Surface haptics was perceived as a novel yet unexpected type of haptic feedback. We discuss the implications for the haptic design of programmable friction displays and provide an initial set of guidelines for this innovative technology.**

***Index Terms*—Haptic design, haptic experience, user interface, haptic feedback, automotive, surface haptics, electrostatic friction modulation.**

I. Introduction

CHANGING demands in future automotive mobility lead to disruptive transformation in automotive interior philosophy. In the age of autonomous driving, the influence of ubiquitous consumer electronic devices and advancements in user interface (UI) technologies ("smart surfaces") cars are expected to transform into rolling entertainment, communications, and recreation hubs with a lounge-like character. Traditional button interfaces cannot keep up with the needs expressed by consumers and stakeholders, such as programmability and compact package size. Nowadays, the design language is characterized by creating a monolithic and harmonic-looking interior using different materials (e.g., textile, wood, etc.), thus avoiding the rugged impression of traditional button interfaces. In short, automotive interiors already do and, in the future, will entail much more flat, seamless surfaces, hence reducing the physical impression from the traditionally rich experience of physical buttons to a mere contact between the finger and a flat display surface.

Automotive applications require interfaces that not only have a high-quality impression, but also a safe, efficient, and potentially eyes-free operation. Paradoxically, the increasing functionality of dynamically changing visual interfaces coupled with the current focus on touch-only interactions requires even more visual attention, posing the risk of visual distraction [1], [2]. Its mere existence in the driver's parafoveal view might already be a source of distraction [3]. A recent German court decision, in which a Tesla driver was fined for an accident caused by adjusting the speed of the windscreen wipers on his Model 3's touchscreen during heavy rain, sparked a debate on the use of in-vehicle touchscreens among interface designers, usability experts, haptic advocates, and consumers [4]–[6]. Despite the growing sophistication of voice- and other input devices, the immediate feedback via direct haptic manipulation still seems to be an important feature of in-vehicle user experience (UX) [7].

The resurgence of tangibles amidst tactually poor interfaces is a recent trend in the consumer electronics market and is also considered as a way forward in automotive user interfaces [8]–[10]. This "tangible turn" [11] revolves around the question of how we can bridge the touch and feel of analog button elements to the digital interface world. Haptic technologies that focus on friction modulation seem especially promising in restoring the tangibility and feel of analog buttons in tactually poor digital interfaces [9], [12], [13]. In contrast to current-state automotive haptic technologies that rely primarily on confirmation haptic feedback upon pressing, friction-based technologies are geared towards giving haptics to a dynamically moving finger, i.e., supporting "haptic search" and eyes-free operation [8]. Despite an automotive application of surface haptics, there are no user-

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TABLE I
OVERVIEW OF LITERATURE ON HAPTIC FEEDBACK IN AUTOMOTIVE USER INTERFACES

Author	Task	Conditions	Device	Main Outcome
Pitts, Williams, Wellings and Attridge (2009) [22]	1) LCT, 2) Touchscreen Use-cases	V, VH, VA, VHA	8.4-inch Haptic Touchscreen with TouchSense	No difference in driving and task performance; Acceptance higher for H than for V
Pitts, Skrypchuk, Weelings, Attridge and Williams (2012) [23]				No difference driving and task performance; preference for multimodal feedback
Pitts, Burnett, Williams and Wellings (2010) [24]	1) Vehicle Following in Driving Simulation, 2) 2D-Target-Selection (Feedback at push)	3 x 2 design, Visual: immediate, delayed, none; V only + VH		No difference in driving performance; Confidence and Hedonic Rating higher for H; perceived difficulty and driving interference lower for H; H reduced total glance time by 19% when V delayed or absent
Pitts, Skrypchuk, Attridge and Williams (2012) [25]				
Rydström, Grane and Bengtsson (2009) [26]	1) LCT, 2) Target-Selection	V, VH_{ridges}, $VH_{ridges+textures}$, $H_{ridges+textures}$	Rotary encoder	Driving performance and mental load did not differ across conditions
Grane and Bengtsson (2012) [27]	1) LCT, 2) Target-Selection	V only, partly corresponding VH, fully corresponding VH, H only	Rotary encoder	"Some" haptics enhanced driving performance, H increased RT; No differences in mental workload
Grane and Bengtsson (2013) [28]	1) LCT, 2) Target-Selection		Rotary encoder	Effectiveness depended on implementation of H; H reduces visual load
Tunca, Fleischer, Schmidt and Tille (2016) [29]	1) Driving Simulation, 2) Target-Selection (search)	Active + Passive Haptic, Blindfolded	Featureless Active + Passive Haptic control panel	No difference for RT, error, and lane deviation higher for active haptics; aesthetical appreciation higher for featureless panel
Tunca, Zoller and Lotz (2018) [30]	1) Driving Simulation 2) Target-Selection (search + push)	Haptic, Non-Haptic, Blindfolded	8-inch haptic touchscreen with four-button layout	Lower error rates, RTs and operational stress for haptic vs non-haptic
Beruscha, Krautter, Lahmer and Pauly (2017) [3]	1) LCT, 2) Target-Selection (search + push)	V, VH, H	7-inch touchscreen with electrodynamic actuator	H reduced eye-off-road time and subjective mental workload
Mullenbach, Bloomer, Colgate and Peshkin (2013) [31]	1) Driving Simulation 2) 1D-Target-Acquisition	V, H, VH	Ultrasonic Friction TPad	Negligible differences for task performance, H reduced eyes-off-road time by 19% and 39%; Participants preferred combined V and H
Weddle and Yu (2013) [32]	Use-cases in parked car	Cadillac Cue Haptic UI vs. non-haptic iPad UI		H perceived easier to use, more pleasant, more confident, more responsive, and more direct
Richter, Ecker, Deisler and Butz (2010) [33]	1) LCT, 2) Input phone number	V, H	8.4-inch screen with linear actuator	H reduced errors and response time; H was more preferred; but very small sample size (n=5)

Note: V = Visual feedback, H = Haptic feedback, VA = Visual-Audio, VH = Visual-Haptic, M = Multimodal, LCT = Lane-Change-Task, RT = Response Time,

oriented haptic studies that use variable friction displays based on electroadhesion in an automotive user context.

A. *Goal of the Study*

The main goal of this study was to provide an initial evaluation of a state-of-the-art electrostatic friction modulation (EFM) device in a dual-task setting with an automotive-related primary driving and a secondary in-vehicle 2D-target-selection task. We aimed to explore the effectiveness of EFM in an automotive setting and reveal strengths as well as weaknesses with respect to haptic feedback design. In contrast to previous studies, we focused on the evaluation of experience-based impressions. Due to the novel and unfamiliar character of EFM in an automotive setting, we were also interested in participants' first-hand responses.

II. A TANGIBLE TURN IN AUTOMOTIVE USER INTERFACES

There is an ample selection of industry-driven demonstrators geared towards a physically rich experience on flat surfaces – mainly in the context of so-called "smart surfaces" [14]. Most automotive OEMs, such as Audi, Mercedes, and Porsche, as well as automotive suppliers, have implemented haptic feedback using solenoid and voice-coil actuators into touchscreens and seamless control panels [15]–[17]. Haptic startups are increasingly trying to implement more innovative haptic approaches, such as friction modulation, that focus on a more feel-and-navigate approach in automotive applications [18], [19].

A. *Friction Haptic Feedback in Automotive User Interfaces*

In general, haptic feedback shows a positive effect on driving performance, visual load, drivers' awareness and thus driving safety across a multitude of guiding and warning use-cases and interior locations [20], [21]. Most haptic warning and assistance systems are embedded at locations that are in direct and continuous contact with the driver, such as a seat or a steering wheel, and thus needing to be categorized as tactile interfaces. Haptic devices are located primarily in the dashboard or middle console. Table I gives a comprehensive overview of the impact of haptic feedback on driving performance and UX in deliberate in-car interaction of direct and remote[1] touch interfaces based on the succinct review in our previous work [8].

To our knowledge, no experimental studies examining electrostatic friction modulation in an appropriate automotive-related context have been reported yet. Transferability of previous results can be boiled down to the following aspects: (1) technology, (2) scenario.

First, most previous automotive UI studies examined the impact of in-vehicle haptic feedback in the context of a multisensory dual-task setting but mainly employed vibration-based haptic screen devices that actuate the entire UI surface. Research literature cannot attest which feedback modality is the most adequate regarding driving and task performance [23], [29]. We suggest that the overall inconsistent pattern of results varies as a function of task difficulty and methodological aspects. It must be considered that task completion times are often higher in haptic-only conditions due to the nature of serial processing which haptic perception is based upon (e.g., tapping a screen based on visual input is inherently faster than using a rotary encoder). The effectiveness of haptic feedback seems to strongly depend on perceived haptic strength [23] and congruency with other modalities [28]. Additional haptic feedback seems to support drivers in keeping their eyes on the road and thus reduce visual distraction [3], [25], [31]. Differences between different modalities in automotive in-vehicle interaction seem to be mainly experience-based (see Table I). Haptic feedback seems to increase confidence in the current mode of interaction and is more accepted than a mere visual interaction. Yet, most participants tend to favor a fully multisensory (visual + haptic + audio) experience. Vibration-based technologies incorporate an often considerable and undesired actuation noise that might alter the overall haptic impression. Latency, which plays a major role in the effectiveness of haptic feedback in interfaces [35], [36] is much lower for EFM than for electro-mechanical actuators. Kim and Schneider [37] speak of *timbre*, i.e., experiential characteristics inherent to a specific technology, as an important design parameter. Hence, conclusions from previous studies using vibration impulses may be limited for novel surface haptic sensations. Friction haptics seems to underlie highly dynamic characteristics [38] and "breaks" common perceptual habits and expectations for haptic-enabled devices. It cannot be fully understood by simple single-shot measurement [39].

Second, most studies using variable friction displays focused on examining human haptic perception and user interaction settings, such as target acquisition, button replacement, or sliding controls (for an overview, see [13]). Initial design explorations for haptic augmentation of digital user interfaces, such as setting an alarm clock and selecting a text, using ultrasonic friction stimuli are reported in [40] and [41]. Zhang and Harrison [42] described performance enhancements for haptic search tasks incorporating electrostatic friction stimuli. However, most of the studies reported by Basdogan, Giraud, Levesque and Choi [13] have been conducted in a lab context using tabletop haptic devices. Research has pinpointed to the importance of context and task requirements for haptic perception [8], so-called "scenario-based" testing [43], and the appropriate evaluation of design [44]. Hence, most previous studies lack context and task information for an ecologically valid evaluation in the automotive context. For example, tactile salience, which is important for identifiable objects in haptic design [45], might vary with different task environments. Pitts, Skrypchuk, Wellings, Attridge, and Williams have discussed the impact of workload on the perceived haptic strength of vibration impulses in a dual-task automotive setting [23]. While electrostatic friction devices may provide convincing haptic feedback in single task settings, it is yet unclear how friction stimuli are perceived when attention is divided. The use of a dual-task setting that sufficiently mimics real-world task demands is essential, which is why we included a primary driving and secondary target-selection task.

In this study, we wanted to examine the application of EFM for "search haptics". With the *Framework of Haptic Processing in Automotive User Interfaces* [8] we provide a four-stage model of in-vehicle haptic interaction. The subsequent stages *Exploration*, *Detection*, *Identification,* and *Usage* pose stage-specific requirements for a successful haptic design. Most of the reported studies (see Table I) have incorporated haptic feedback at the *Usage* level. Even though the secondary task entailed a target-selection task in many cases, haptic feedback has been limited to haptic clicks as confirmation, based mostly on a simple skeuomorphic design approach [10]. This might be because vibration-based actuators and the way they are integrated into haptic systems are far more suitable to recreate a convincing button press sensation (user input in z-axis) than surface features, such as edges (user input in x/y-axis). Only a limited number of studies has so far explicitly focused on the *search haptics*-part of the framework, i.e., *Exploration*, *Detection*, *Identification*, for example, by haptically augmenting edges to enable eyes-free "searching" for interactive elements on touchscreens [3], [30]. Tunca, Fleischer, Schmidt, and Tille [29] used an exploration-focused selection task to compare a flat haptic-enabled and passive haptic control panel. EFM relies on active tangential user input. It is more suitable for augmenting interface elements during the *Detection* and *Identification*-level to help "finding" interactive elements. Hence, to measure the effectiveness of the haptic approach in an ecologically valid manner, the secondary task needs to be focused on a feel-and-navigate paradigm to leverage technological characteristics.

III. Method

The study was conducted according to the principles expressed in the Declaration of Helsinki and according to the ethical principles of the German Psychological Society (DGPs) and the Association of German Professional Psychologists (BDP). The general study design (psychophysical testing) was

1. In direct touch, the location of input (control) and output (representation) of Graphical User Interfaces (GUI) coincide [34]. In contrast, remote touch refers to the control of a GUI via an external interface, such as a touchpad.

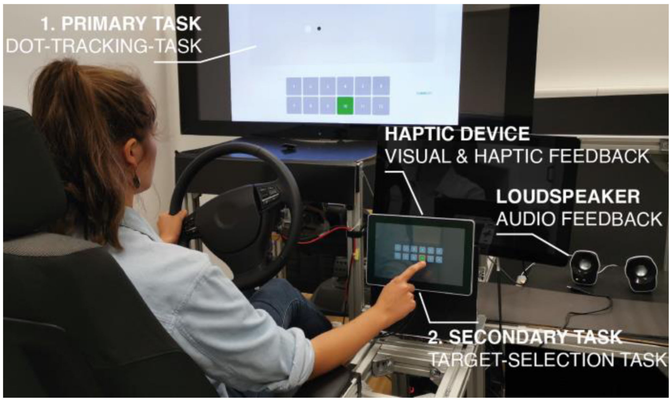

Fig. 1. The study included a dual task setting in a medium-fidelity interior mock-up. The primary screen in front of participants displayed the primary task and the target item. The selection task was performed on the haptic touchscreen device located in a center stack position. Additional speakers were used for audio feedback.

given ethical approval by the local ethics committee of the University of Bamberg.

A. Participants

Thirty-two participants took part in the study. They were between 20 and 60 years old ($M_{\text{age}} = 33.2$ years, $SD = 11.4$); 12 were female and 20 were male; 28 were right-handed, two left-handed, and two ambidextrous (measured via self-assessment). All participants worked in the broader field of the automotive industries, but were naïve to the aims of the study and had not gone through special training in haptic perception. Ten participants had more extensive experience or previously worked with active haptic devices in various contexts. Thirty participants owned a device with active haptic feedback, mostly smartphones with a linear resonant actuator. Sixteen participants reported they do not drive a vehicle with a built-in touchscreen. Seven participants stated to use the in-vehicle touchscreen daily, one multiple times a week, six once a week, and two of them only rarely.

B. Apparatus

1) Interior Mockup: We used a seating bucket consisting of an adjustable car seat, a steering wheel, a primary screen, and a secondary screen connected to a host computer. The apparatus did not include any environmental influences, such as sound or vibrations while driving. The experimental software and Haptic Engine ran on the host computer with a Windows 10 operating system (see Fig. 1). The seating bucket retained the approximate geometrical dimensions of a car interior with a steering wheel, a center console, and the haptic device that mimicked a center-position infotainment display. The primary screen in front of the participants displayed the driving task. The steering wheel was a Logitech Momo Racing Wheel refitted with a steering column to house a standard automotive steering wheel. The force feedback functionality was switched off at all time.

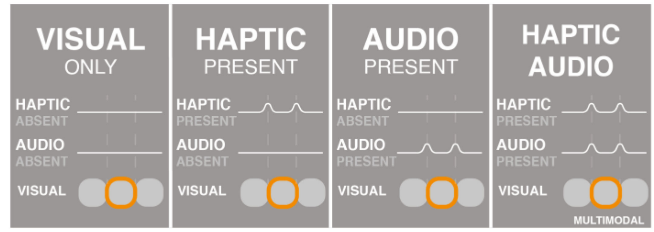

Fig. 2. The study entailed four different feedback conditions with haptic and audio feedback either present or not. Visual feedback in the form of an orange item contour was always present.

2) Haptic Device: The haptic device used in the study was a MimoVue TanvasTouch 10.1-inch Development Kit monitor. It is an off-the-shelf electrostatic friction display based on the principle of electroadhesion, which can be acquired via Tanvas [46]. Spatial resolution of the display is 1280×800 pixels. A single pixel equals 170 μm. The haptic effects are created by modulating the friction coefficient of the user's moving finger due to electrostatic attraction by regulating the voltage applied to an additional electrode layer on the device's cover glass. Feedback upon static touch is not possible with this device and will not be discussed further in this study. A more detailed description of the technical stack can be found in [12]. For an extensive explanation and review of the employed actuation principle, we refer the reader to [13], [12] and [47].

3) Feedback Modalities: The study implemented a 2×2 design of feedback conditions (factors *haptic/audio* with levels *absent/present*) to assess the effectiveness of the haptic feedback. Haptic or audio feedback was either present or absent. Visual feedback was always present. Feedback was given at transition events when selecting elements in a 2D button matrix (see Figs. 2 and 4). Element size was 15.3×15.3 mm (90×90 pixels) with an edge width 4.08 mm (24 pixels). The visual feedback consisted of an orange item contour that depicted the selected item in the matrix and was included in all feedback conditions (see Figs. 2 and 3B). The audio feedback consisted of a "poc"-sound (10 ms, like a dull knocking sound) implemented in the touchscreen interaction in current BMW models. The haptic feedback included a two-step approach: (1) white-noise button texture in the search-stage and (2) a low-high-low friction change (1.87—0.34—1.87 mm; 4.08 mm total width) at transition events when selecting items in the matrix. The white-noise texture enabled participants to blindly "acquire" the start element in each trial. The matrix elements consisted of high-friction areas (see Fig. 3) with low-friction transitions.

The haptic feedback was based on a pre-study with 16 participants in which we compared the effectiveness of different haptic grid configurations. In this pre-study, we identified low friction transitions (width 5.1 mm) with high-friction matrix items as optimal. The final iteration of the haptic feedback, which integrated insights from other internal lab-based studies, is shown at the bottom right side of Fig. 3C. We chose the item elements to have a high friction area. The rationale is that the higher friction parts during the exploration movement may already hint towards an interactive area versus the lower

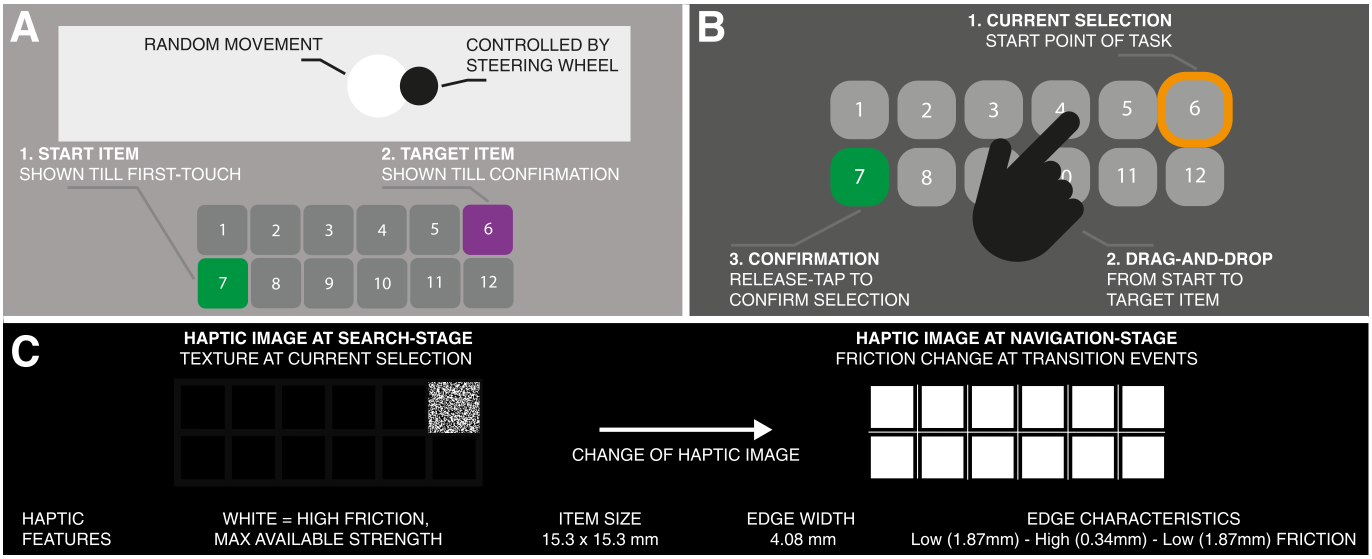

Fig. 3. Depiction of the A) primary screen with the primary driving task and a visual depiction of the 2×6 matrix with start and target item to be selected during interaction and B) secondary haptic screen with the secondary target-selection task. C) Depicts the haptic feedback during the search and navigation task.

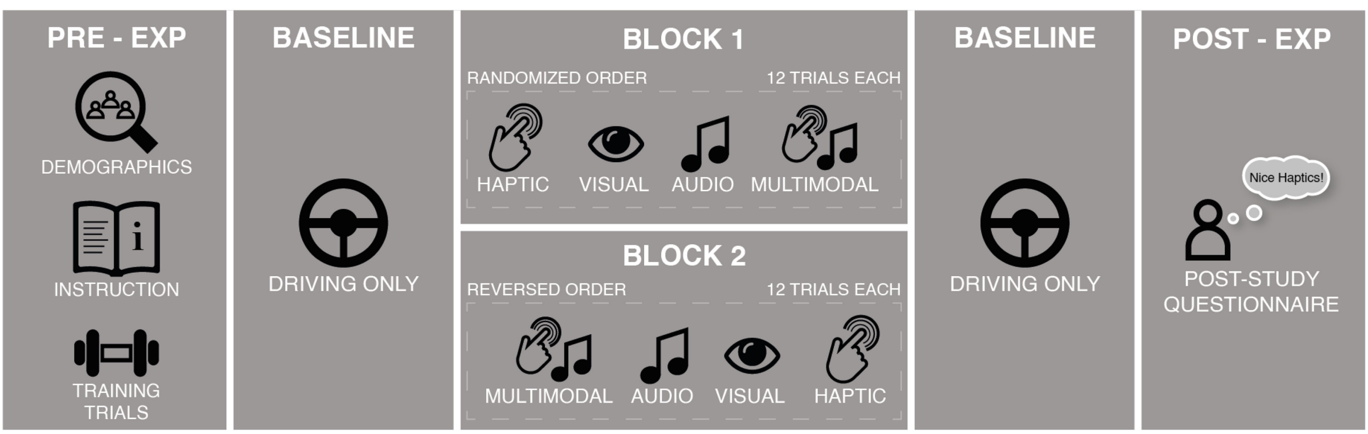

Fig. 4. Each study session consisted of a pre-experimental, two baseline (driving only), two experimental (each including four different feedback conditions with 12 trials each) and a post-experimental block.

friction part on the rest of the screen. A report of the pre-study is included in the supplementary material.

C. *Dual-Task Setting*

This study included an automotive dual-task setting with a primary driving-related task that required constant attention and manual manipulation of the steering wheel as well as a simultaneous secondary target-selection task to mimic an appropriate driving context for haptic evaluation.

1) Primary Driving Task: The primary task was shown on a screen directly in front of the participants (see Fig. 3A). Participants were instructed to focus on the primary task and to restrict themselves from looking at the secondary touchscreen – like while driving a car. As an analog to a typical lane-keeping task, we employed a dot-tracking-paradigm that requires continuous attention and steering, thus providing essential information about deviance from an ideal tracking trajectory. This deviance helps to operationalize error proneness due to a secondary task. We chose to implement this highly controlled paradigm as opposed to a more realistic driving task to reduce the complexity of experimental design and handling as well as to counteract vulnerability to systematic strategic and learning effects [48], [49], [23]. The employed paradigm included a white dot, which was moving randomly on a horizontal axis, and a smaller black dot, controlled by turning the steering wheel. The participants' task was to continuously align the black dot. The task's difficulty could be systematically varied by changing the range and speed of the white-dot-movement. We decided to set the task's difficulty to an intermediate level which was evaluated via pre-study expert evaluations. In the post-study questionnaire, participants stated that the task was challenging but still appropriate and immersive. One of the participants' descriptions seems very fitting: "as if you were driving on a curvy countryside road."

2) Secondary Target-Selection Task: The secondary task entailed a target-selection task. Participants performed the selection while simultaneously focusing on the primary task.

We implemented a tripartite trial procedure of (1) finding the start button, (2) navigating to and (3) confirming the target item (see Fig. 3B) to reflect all the key challenges of operating a car's functions and still enabling participants to fulfill the task similarly to a "blind control" [8]. A 2×6 matrix of elements was presented on the secondary touchscreen device. The 2×6 matrix, with the respective start (green) and target (purple) items, was also displayed on the primary screen in front of the participants (see Fig. 3A).

At the beginning of each trial, only the start element was shown on the secondary screen and augmented by a haptic texture or an audio signal (see Fig. 3C). The start item was randomly located at one of the corners of the item matrix (i.e., item 1, 6, 7, or 12). Participants were able to explore and feel the start button. Upon activation of the start button, the touchscreen changed to a "normal" interaction stage which showed the 2×6 matrix as depicted in Fig. 3B. The target item was purple in the 2×6 matrix in the primary screen in front of the participants. (see Fig. 3A). We did not show the target item on the secondary screen to minimize visual attention and recreate an "intention to control" as natural as possible – in everyday interaction the desired function is not highlighted but defined by a user. Participants had to select the target by dragging the cursor to the target item. This drag-and-drop paradigm ensured that participants really engaged with the haptic and audio feedback and did not just press the target item – as they would potentially do with a regular touchscreen. It also standardized trials across all feedback modalities. The current selection was highlighted by an orange item contour (see Fig. 3B). Confirmation was performed by releasing-and-tapping at the desired item. The trials only proceeded upon correct confirmation of the target item. Participants were able to interrupt the selection procedure. Once participants lifted their finger or left the item matrix, the interaction restarted at the search stage with the last-selected item augmented via a haptic texture or sound – similar to the initial start item. There was no time restriction.

D. Dependent Variables

We followed a multimethodological approach for a holistic assessment of UX. Objective measures included response time for performing the primary task, performance on the primary task, and erroneous confirmations. To complement these objective measures, we included a post-block UX questionnaire and a post-study questionnaire. Table II describes the questionnaire items that were presented after the completion of every feedback block. In the post-study questionnaire, participants were asked (1) to rank the feedback modalities based on their preferred interaction, (2) to rate the perceived strength of the haptic feedback on a scale from 1 (*very weak*) to 7 (*very strong*), and (3) to provide general feedback on the study, the task and how they felt about the different feedback modalities in the form of open questions.

TABLE II
POST-BLOCK USER EXPERIENCE QUESTIONNAIRE

Variable	Question
Pleasantness	*How **pleasant** is the feedback?*
Perceived Quality	*How do you rate the **quality** of the feedback?*
Precision	*How **precise** is the feedback for navigation in a grid of elements?*
Annoyance	*How **annoying** is the feedback?*
Fitting	*How **fitting** is the feedback for navigation in a grid of elements?*
Difficulty	*How **difficult** was the selection task using the touchscreen?*
Interference	*How much did the secondary selection task including the feedback **interfere** with the main driving task?*
Visual Distraction	*How much did the secondary selection task **visually distract** from the driving task?*
User Experience	*Does the feedback enhance **user experience**?*

Note: Rating scale ranged from 1-7 with the anchors adjusted to the item, for example: 1 representing *not at all* and 7 *very pleasant*.

E. Procedure

The experiment was conducted in a quiet and specially prepared room. Upon arrival, participants were asked to wash and disinfect their hands. Participants were made aware of their right to withdraw themselves and their data from the study without consequences and without giving any reasons. Written informed consent was then given by each participant. The experimenter introduced participants to the procedure of the study and collected demographic data. Participants were instructed to find a comfortable seating position while the experimenter presented the experimental task, trial procedure, and the post-block experience questionnaire (see section Dependent Variables). Participants were told to imagine sitting in a car while driving and controlling a car's functions but prioritizing the primary dot-tracking task to perform as well as possible. In a pre-study training block, which included haptic feedback, participants familiarized themselves with the study setup and the haptic device. The experimenter did not explicitly introduce participants to the haptic feedback. The goal was to establish an ecologically valid test setting by not favoring a specific kind of feedback modality and preventing the influence of any potentially biasing *a priori* evaluations. The experimental session consisted of an initial "Driving only" block, followed by two experimental blocks and a concluding "Driving only" block. Each of the feedback blocks was presented twice in a randomized and reverse order for every participant. The experimental procedure is depicted in Fig. 4. Each block consisted of twelve trials. The driving-only trials were terminated after twelve seconds. The trials in the feedback blocks proceeded after confirmation of the correct target item. After the experimental session, participants were asked to complete the post-study questionnaire. The session was concluded by clarifying any open questions. The experimenter cleaned all areas of contact prior to the arrival of the next participant. A single session took about 60 minutes.

IV. RESULTS

Error bars in the figures depict one standard error of the mean. Results were analyzed using the statistical software R 4.0.5 [50]. Feedback conditions are described by factors

TABLE III
LINEAR MIXED MODELS FOR TASK PERFORMANCE, RESPONSE TIME AND ERRONEOUS CONFIRMATIONS

Primary Task Performance					
Fixed.Effects	**Estimate**	***SE***	***df***	***t***	***p***
(Intercept)	**0.002443**	0.000425	55	5.75	**<0.001**
HapticPres	-0.000080	0.000180	3036	-0.44	0.66
AudioPres	-0.000091	0.000180	3036	-0.50	0.62
Block	0.000020	0.000028	3036	0.71	0.48
HapticPres: AudioPres	-0.000157	0.000255	3036	-0.62	0.54
Response Times					
(Intercept)	**5784.79**	451.84	39	12.80	**<0.001**
HapticPres	212.65	126.08	3036	1.69	0.09
AudioPres	**281.49**	126.08	3036	2.23	**0.03**
Block	**-261.75**	19.45	3036	-13.45	**<0.001**
HapticPres: AudioPres	**-393.97**	178.30	3036	-2.21	**0.03**
Erroneous Confirmations					
Fixed.Effects	**Estimate**	**SE**		***z***	***p***
(Intercept)	**0.888287**	0.30909		2.87	**<0.001**
HapticPres	-0.050087	0.07636		-0.66	0.51
AudioPres	-0.074568	0.07685		-0.97	0.33
Block	-0.006513	0.01190		-0.55	0.58
HapticPres: AudioPres	0.074561	0.10901		0.68	0.49

Note: *SE* = Standard Error, bold number indicates $p < 0.05$, Erroneous Confirmations were analyzed using a generalized linear mixed model.

Haptic and *Audio* and factor levels *absent* and *present*. Participants performed every feedback condition twice, which is indicated by the *Block*-variables (see Fig. 4). All models included *Haptic:Audio* as an interaction-term. The participants-variable was defined as a random effect in all models. All significance tests were based on an alpha-level of 5%.

A. Objective Variables

1) Performance Primary Task: Performance in the driving task was assessed using the dot-tracking-task. The relative position of both dots was defined by values between -1 and 1. The performance measure was based on the aggregated deviation of both dots. The mean squared deviation for every feedback block was used for the statistical analysis. A linear mixed model with feedback factors *Haptic* and *Audio* and *Block* as predictors were fitted using the *lmer*-function [51]. Table III describes the results from the model. None of the factors yielded a significant result. All feedback blocks differed from the driving-only blocks (Fig. 5).

2) Response Times: Response times were measured from the first finger-down event until the correct activation of the indicated target item. Mean response time ranged from 4083 ms (*HapticAbsent & AudioAbsent*) to 4365 ms (*HapticAbsent & AudioPresent*). A linear mixed model based on response time was fitted using the *lmer*-function. Table III describes the results from the linear-mixed model based on the response times. The block predictor showed a significant result ($\beta = -261.7$, $t\,(3036) = -13.45$, $p < .001$). The negative slope indicates that participants were faster in the second iteration of the feedback blocks (Fig. 4). *AudioPresent* ($\beta = 281.49$, $t\,(3036) = 2.23$, $p = .03$) as well as the interaction term ($\beta = -393.97$, $t\,(3036) = -2.21$, $p = .03$) yielded significant results, meaning *AudioPresent* yielded higher RTs when *Haptic* is *absent*.

3) Erroneous Confirmations: Erroneous confirmations represent activations of non-target items in the matrix until confirmation of the correct target. For statistical analysis, we used the aggregated number of erroneous confirmations per block. A generalized linear regression model using *glmer*-function (family parameter set to poisson) with the factors *Haptic*, *Audio* and *Block* as well as an interaction term as predictors was fitted (see Table III). No factor yielded a significant result.

B. UX-Variables

Fig. 6 shows mean ratings for all items with relation to the experience-based questionnaire that participants filled in after each feedback block. To compare the feedback condition, we fitted a cumulative link mixed model using the *clmm()*-function from the *ordinal* package [52] with factor *Haptic* and *Audio* as well as the interaction *Haptic:Audio* as predictor with each of the UX-variables as a criterium. The results are shown in Table IV. All scales showed two significant main effects (*Haptic* and *Audio* is significant, but not the interaction term) except for *Annoyance* (only *Audio* significant) and *Enhancement,* which showed a significant result for the interaction term. In this case, interpretation of the *Audio* main effect depended on the factor level of the *Haptic* factor ($\beta = -1.45$, $z = -3.11$. $p < 0.01$). The *Audio*-factor only yielded a difference in case haptic was not present.

C. Post-Experimental Data

The post-experimental data included (1) a preference ranking ranking of feedback modalities, (2) perceived haptic strength, and (3) qualitative data from the open post-experimental questions. Fig. 7 depicts the frequency of rank assignments for the different feedback modalities. Based on a Kruskal Wallis test, the modalities differed regarding their ranking ($\chi^2 = 27.43$, $df = 3$, $p < 0.01$). The visual-only condition was least preferred. More than half of the participants preferred the multisensory modality (*Haptic* and *Audio present*). The mean perceived haptic strength was $M_{\text{haptic}} = 4.14$ ($SD = 1.57$). Three participants reported they did not consciously feel haptic feedback during the tasks. The verbal responses were categorized using categories that were established in our previous work [38].

V. DISCUSSION

The present research reports an initial evaluation of an electrostatic friction display in an automotive-related context. Results indicate that there were no consistent differences between feedback modalities regarding primary and secondary task performance. Feedback modalities mainly differed on the

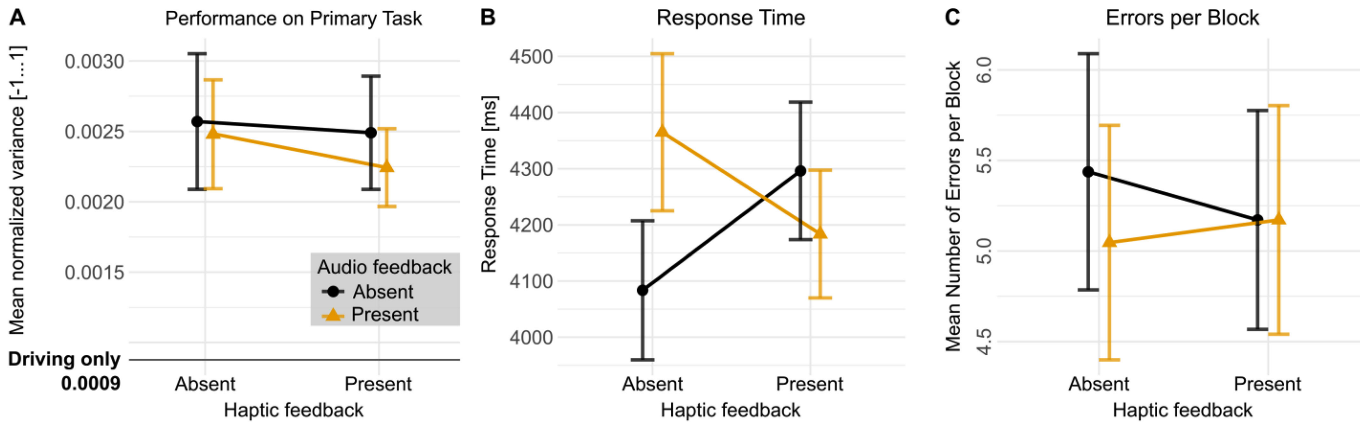

Fig. 5. Line plots for (A) performance primary task, (B) response times and (c) erroneous confirmations. Error bars present $\pm$ 1 standard error of the mean (SEM).

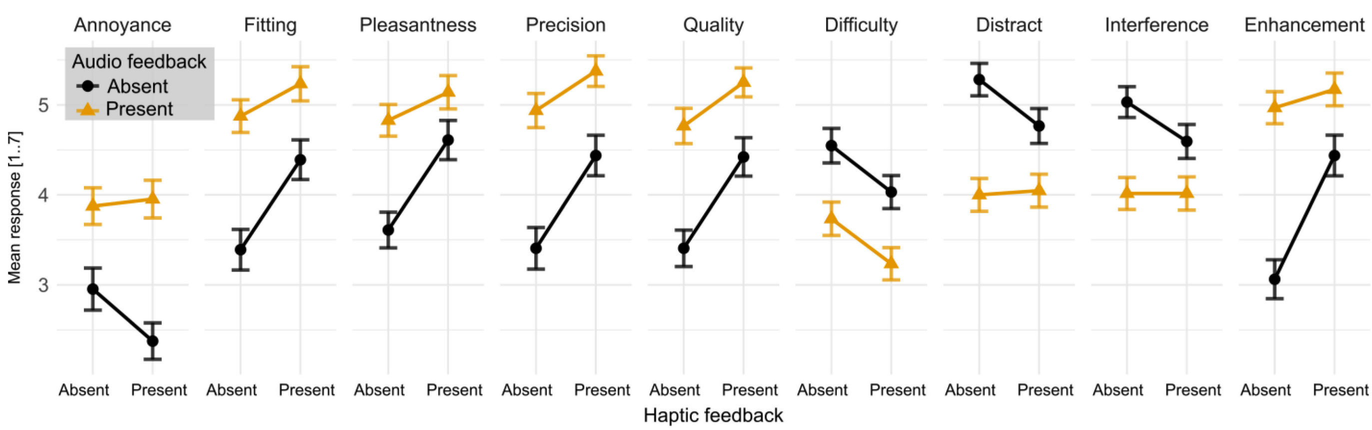

Fig. 6. Mean response values of user experience variables based on feedback modalities. Error bars represent +/-1 standard error of the mean (SEM).

experience level. In general, any additional feedback was perceived as superior to mere visual feedback. Overall, participants preferred multisensory feedback. The audio feedback seemed to be more beneficial for UX than the electrostatic friction feedback. However, the audio feedback was perceived to be more annoying than haptic feedback. In general, participants perceived the haptic feedback as too weak, which might have influenced the experience evaluations. The following section will discuss these results in greater detail.

A. *Performance and Experience*

The results indicate that feedback modality had no consistent influence on driving and task performance (see Fig. 5). This finding seems to be counterintuitive at first sight. One explanation could be that the dot-tracking paradigm was not fully suitable to yield significant differences. Despite a highly controlled environment to counteract methodological issues from commonly used approaches, the dot-tracking might have been too abstract. It does lack some characteristics that constitute a typical driving situation, such as anticipatory driving or environmental noise and vibration. Also, the difficulty level of the primary task might have been inappropriate. On the other hand, feedback modalities might not have had an influence on performance as participants may have been too experienced in an automotive multitask setting. In general, this pattern of results fits very well with previously described literature (see Table I). Despite using higher fidelity driving simulations and confirmation-focused tasks, previous studies also did not report a consistent impact of feedback modality on objective measures. The impact of haptic feedback on performance measures may be based on different aspects, such as visual distraction. Gaze behavior operationalized via eyes-off-road time or number and length of fixations and saccades may provide valuable insights on distraction [3], [31], [25].

A mere performance-based evaluation neglects the holistic nature of user interaction and its implications on UX as differences between feedback modalities seem to be mainly experience-based. Any additional feedback to a visual-only baseline enhanced UX. It made the interaction feel more pleasing, precise, higher quality, less difficult, less distracting, and less interfering. Haptic and audio feedback felt more fitting than mere visual feedback. Table I reports similar findings: haptic interfaces are more accepted, reduce subjective workload and increase user's confidence.

Another intriguing finding was the positive impression of audio feedback compared to the haptic impression. Audio seemed to have a bigger impact on UX than the haptic feedback.

TABLE IV
CUMULATIVE LINK MIXED MODEL WITH UX-VARIABLES AS CRITERIA

Modality	Estimate	*SE*	*z*	*p-value*
Annoyance				
HapticPresent	-0.65	0.34	-1.92	0.055
AudioPresent	**1.36**	0.34	4.05	**<0.001**
HapticPresent: AudioPresent	0.73	0.46	1.59	0.111
Fitting				
HapticPresent	**1.31**	0.35	3.78	**<0.001**
AudioPresent	**1.93**	0.34	5.59	**<0.001**
HapticPresent: AudioPresent	-0.67	0.46	-1.45	0.148
Pleasantness				
HapticPresent	**1.43**	0.34	4.17	**<0.001**
AudioPresent	**1.61**	0.33	4.83	**<0.001**
HapticPresent: AudioPresent	-0.85	0.46	-1.83	0.067
Precision				
HapticPresent	**1.40**	0.34	4.08	**<0.001**
AudioPresent	**2.15**	0.35	6.07	**<0.001**
HapticPresent: AudioPresent	-0.83	0.47	-1.77	0.076
Quality				
HapticPresent	**1.37**	0.34	4.09	**<0.001**
AudioPresent	**1.81**	0.34	5.37	**<0.001**
HapticPresent: AudioPresent	-0.77	0.46	-1.68	0.094
Difficulty				
HapticPresent	**-0.73**	0.33	-2.20	**0.028**
AudioPresent	**-1.32**	0.34	-3.88	**<0.001**
HapticPresent: AudioPresent	-0.04	0.46	-0.09	0.931
Distract				
HapticPresent	**-0.79**	0.34	-2.30	**0.021**
AudioPresent	**-2.10**	0.35	-5.98	**<0.001**
HapticPresent: AudioPresent	0.87	0.47	1.87	0.062
Interference				
HapticPresent	**-0.70**	0.34	-2.06	**0.039**
AudioPresent	**-1.81**	0.35	-5.18	**<0.001**
HapticPresent: AudioPresent	0.70	0.47	1.50	0.135
Enhancement				
HapticPresent	**1.79**	0.35	5.13	**<0.001**
AudioPresent	**2.40**	0.36	6.75	**<0.001**
HapticPresent: AudioPresent	**-1.45**	0.47	-3.11	**0.002**

Note: SE = Standard Error, bold numbers indicate $p < 0.05$.

The visual-audio condition was ranked higher than the visual-haptic condition. Previous studies describe similar findings [22], [23]. We propose two explanations: Firstly, users may be more accustomed to audio feedback as it is – in contrast to haptic feedback – already widely implemented in consumer devices and in-vehicle touchscreens. Secondly, the haptic feedback seemed to be perceived as too weak to have a similar impact on UX as audio feedback. Three participants reported they did not feel the haptics. A repeated analysis dropping those three participants showed slightly, but not substantially different results. Interestingly, all participants felt the haptics when they were shown a single-task demo application after the study. Averaged perceived haptic strength was 3.8 on a scale from 1 (*weak*) to 7 (*strong*). In the post-study questionnaire, about half of the participants wished for stronger haptics. Pitts, Skrypchuk, Wellings, Attridge and Williams [23] also concluded that despite prior validation, the vibration feedback they used was not strong enough to convey stronger feedback than the audio impression. Haptic feedback in this study was based on results from a pre-study (see supplementary material) as well as insight from lab-internal observations. As perceived haptic strength seems to be a crucial aspect for its effectiveness in UX [38], we would like to discuss potential reasons for an overall low perceived strength of the electrostatic impulses.

The implemented haptic device is still in development and may thus be restricted in terms of maximum available haptic strength. While it delivers convincing high-fidelity haptics in single-task table-top settings, perceived intensity deteriorates once a cognitively demanding primary task is introduced. This observation highlights the importance of context information and task demand for design and haptic evaluations [8], [53], [43]. Carbon already stated that *“Design without context liquidates meaning”* [44]. MacLean and Hayward [45], [54] highlight the importance of context on *tactile signal salience*. In single-task settings, participants allocate their attention to haptic impulses felt on a display, while in the automotive-relevant setting attention is divided between primary and secondary tasks. As haptic stimuli were involved in a secondary task, they may potentially require a higher tactile salience. The haptic impression might have also been “overshadowed” by the clear and prominent audio signal. Following the notions on multisensory integration the comparatively weak haptic impression might have been hampering its “trustworthiness” and “appropriateness” for the selection task [45], [55], [56]. Overall, the development of more capable devices is required to overcome the hurdle of divided attention. Even though haptic saliency was limited in our haptic device it sheds light on some relevant haptic design considerations in the automotive context.

Additionally, EFM is a novel kind of haptic feedback that may have mismatched participant’s perceptual habits [44]. They were unfamiliar with the friction sensation, which was often confounded with grease from fingerprints. Also, friction stimuli contradicted some of the participants’ expectations towards haptic-enabled touchscreen feedback. Some of the participants expected vibration impulses. All these factors might contribute to a generally weak haptic impression for some participants. In an earlier study [38] we proposed friction stimuli might require familiarization and habituation which goes beyond pure mere-exposure to be fully accepted in UI contexts. Our results indicate that participants required less time for the selections after more training, but the number of erroneous confirmations and performance in the driving task remained on a similar level (indicated by the Block-variable Table III). It seems that with more training participants became faster, but didn’t do “better” selections or were less distracted. The drop

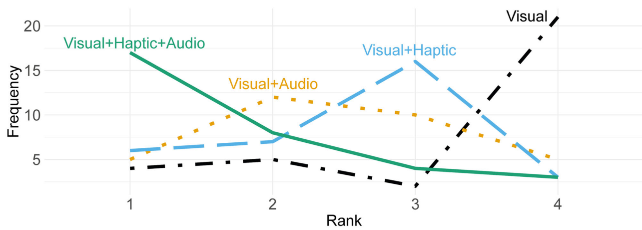

Fig. 7. Frequency data for the modality preference ranking.

in response times does not necessarily depend on feedback modality. Designers and practitioners need to be aware that electrostatic friction modulation, as well as haptic feedback via sliding, might be a novel and unfamiliar experience for most users in the upcoming years. Future studies might use familiarization paradigms, such as the *Repeated Evaluation Technique* (RET) [39] that involve a deeper evaluation phase to capture the long-term effects of innovative interfaces.

Association-based insights are hardly considered in perception and interaction-based studies, even though it is essential for product experience as it might affect a product's long-term appreciation [57]. A few participants explicitly reported negatively connoted descriptions including (mild) "electroshock", "sizzle on the finger", or "like a dirty surface" that have already previously been described [38].

Multisensory feedback has been the most preferred type of feedback (see Fig. 7). In demanding contexts, complementary and redundant haptic and audio cues are crucial to support user interaction and reinforce task demands [45] but also to involve the user holistically. This is substantiated by one participant's response ("I like the multisensory feedback. It creates engagement") and has been well documented in previous literature [22], [23] as well as general design guidelines [58]–[60]. EFM lacks the by-product actuation noise of vibration-based technologies, which gives designers additional degrees of freedom in sound design. Yet designing a convincing haptic impression becomes more challenging as designers cannot rely on sound to alter the haptic impression. Though the audio feedback was valuable for selecting the correct item, it was perceived as more annoying than haptic and visual feedback, which might negatively impact product experience in the long term. It must be noted that the experimental setting did not include any environmental noises (e.g., engine, traffic, etc.) usually prevalent while driving that might modulate salience and annoyance of the audio feedback.

B. Limitations

There are some limitations to the study setup we would like to address. An obvious limitation is linked to perceived haptic strength. The study was performed with a first-generation EFM development kit, whose technology is under constant development [46]. Some participants reported difficulties regarding position sensing and haptic strength, which might follow the dependence of surface haptics on the moisture content of the skin [13], [61]. This might have been influenced by participants' dry skin due to frequent hand cleaning and disinfecting during data collection (June 2020). Precision in terms of finger sensing as well as perceived haptic strength might have also been limited by the current hardware and firmware version. Yet, most participants did not have any problems at all. Albeit using a prototype-level device, this initial evaluation poses the opportunity to identify risks and potentials for further technological developments.

Other limitations refer to the studies' methodology. The study setup did not include any measures of visual distraction to control for gaze behavior. The "Visual Distraction"-variable was introduced to capture participants' perceived visual distraction. Previous studies have shown a positive influence on gaze behavior in driving tasks [3], [25], [31].

This study only assessed friction stimuli in a 2D-target-selection task. Studies have shown that friction haptics may also be useful in simpler 1D-target-acquisition tasks, but also more complex interaction use-cases [31], [40], [41].

Some participants pointed to the limited realism of the primary and secondary task as well as hardware setup. The primary goal of this study was to provide an initial evaluation of an up-to-date EFM device using an appropriate driving task with a highly systematic and standardized methodology. The "drag-and-drop"-paradigm used in the selection-task differs from a tap-and-touch-centric approach but ensured that participants felt the transition feedback and could not "skip" the navigation-part of the interaction. Also, additional noise or vibrations while driving might increase realism and should be considered to be included in future studies.

The study included a limited set of UX-variables, that are crucial for an initial UX evaluation. The variables were based on previous studies [22]–[24]. We did not include existing UX-questionnaires as this study focused on exploring the impact of the feedback modality rather than the interaction use-case itself. Nevertheless, variables such as pleasantness, annoyance, etc., allow for an initial user-centric evaluation of the friction stimuli. We encourage other researchers to validate our findings using higher-fidelity interface prototypes and testing environments.

C. Outlook

Designing enjoyable and efficient interfaces that require little visual attention remains a challenge for automotive UI designers. This study indicates that audio and friction haptics may be an essential piece to the puzzle, yet haptic feedback is no omnipotent remedy to reduce visual distraction and enhance UX. What it means is that simply adding haptic feedback does not make it a good interface. What is still missing is a proper psychologically-driven framework of translating the tangibility of high-quality analog haptic impressions to a digital interaction space. Understanding haptics from a user-centric perspective is crucial as user associations, experiences, expectations, and context underlie the functional assessment of haptic stimuli [53], [62], [44]. For example, while high-frequency textures might be salient, negatively connoted associations potentially deteriorate long-term appreciation. In addition, friction stimuli are still a novel haptic quality that the majority of users has no experience with to fully appreciate its effectiveness.

UI-elements, such as the use of dedicated physical buttons, information hierarchy, element size on screens, and prioritization of voice interfaces potentially have a bigger contribution to eyes-free operation than mere haptic feedback on visual interfaces. While automotive voice interfaces become increasingly versatile from a technological perspective and thus alleviate mental and visual demand, a large German customer survey [7] indicates that users still might have preconceptions towards speech interaction and prefer other - mostly haptic - ways of interaction. We hope that future interaction research and engineering will incorporate a deeper psychological and user-centric approach to accommodate psychological aspects, such as habituation, haptic experience, user associations, expectations, and context instead of following a techno-centric approach. Future research needs a clear focus on actual user needs instead of a techno-centric approach during interior development.

This study showed the overall positive influence of surface haptics for use in an automotive 2-D-target-selection use-case. However, fully software-defined haptics, such as EFM, allow for a much broader application of haptic use cases, such as the haptic augmentation of virtual items via different surface features [63], fully augmented sliders, turn dials and toggles [19], [64].

VI. Conclusion

This study provides an initial evaluation of electrostatic friction modulation in an applied automotive multitask setting and preliminary guidelines based on these findings. Focusing on objective measures neglects a holistic assessment of haptic feedback in user experience contexts. Participants preferred multisensory feedback. Despite using a prototype-level device, we argue that surface haptic feedback benefits user experience design in seamless tangible user interfaces as it allows to restore the tangibility otherwise only known from physical buttons. We encourage future research to further explore the design space of surface haptics applications in automotive.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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