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The influence of tactile feedback in In-vehicle central control interfaces on driver emotions: A comparative study of touchscreens and physical buttons

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ABSTRACT

Touchscreen in-vehicle central control interfaces are rapidly replacing traditional physical buttons. However, the differences in the effects of tactile feedback between touchscreens and physical buttons on driver emotions are unclear. This study used a simulated driving experiment to investigate the effects of tactile feedback mode and intensity on driver emotion using the Self-Assessment Manikin (SAM). The results showed that tactile feedback mode, intensity, and difficulty of non-driving-related tasks (NDRTs) significantly affected drivers' emotional states. Touchscreen tactile feedback elicited a more positive emotional state than physical button tactile feedback. The intensity of touchscreen tactile feedback is positively correlated with driver emotional valence. However, higher-intensity physical button feedback decreases driver emotional valence, particularly when drivers are engaged in complex NDRTs, and the difference due to feedback intensity is insignificant. The study's results could help automakers intervene by designing tactile feedback to enhance the emotional experience of the driver's in-vehicle interaction interface.

1. Introduction

With the rapid development of the automotive industry, the in-vehicle central control interface is now the primary human-machine interaction (HMI) interface in the driving environment. It has become the focus of global automotive engineering research (Ziakopoulos et al., 2019). Many drivers will use the HMI interface to complete non-driving-related tasks (NDRTs) during driving. Since driving tasks require focused attention and high visual engagement, researchers and automobile manufacturers are actively adopting tactile feedback technologies to assist drivers in effective HMI (Breitschaft et al., 2019; Gaffary and Lécuyer, 2018).

However, the sales of in-vehicle central touchscreens have increased rapidly in recent years and have replaced traditional physical buttons in large numbers (Statista, 2017). In response to this trend, many studies have compared the effects of touchscreens and physical buttons tactile feedback on drivers, such as visual attention management (Suh and Ferris, 2019), hazard negotiation performance (Deng and Kaber, 2022) and cognitive load (Nagy et al., 2023). Notably, a complete theoretical framework has yet to explain the impact of tactile feedback mode (TFM) and tactile feedback intensity (TFI) from the in-vehicle central control interface on drivers' emotions. Studies have explored the effects of TFI on drivers' subjective and emotional values (Wellings et al., 2010; Vieira et al., 2017; Gaspar et al., 2017; Valverde et al., 2019), which mainly focused on physical buttons and did not compare the tactile feedback from different modes. Since tactile feedback brings perceptual differences to users (Lederman and Klatzky, 1987, 2009), and emotional states have a critical influence on driver decision-making and behaviour (Steinhauser et al., 2018; Zhou et al., 2022), it is necessary to compare the different opportunities and challenges brought by TFI in physical button and touchscreen interfaces of in-vehicle central control interface on drivers' emotions.

This study aims to investigate the effects of TFM and TFI on drivers' emotions. To achieve this, we collected 42 participants' subjective emotional responses to tactile feedback in in-vehicle central control interfaces. In addition to measuring emotional states, NDRT performance (efficiency and accuracy) was utilized to assess the relationship between task performance and driver emotional states. The results of this exploratory study will help provide theoretical support from the laboratory for the emotional design of tactile feedback for in-vehicle central control interfaces.

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1.1. Tactile feedback for in-vehicle central control interface

Tactile feedback in HMI has been studied extensively (Chung et al., 2010; Dabic et al., 2013; Rhiu et al., 2018). In the in-vehicle central control interface, drivers can use various input channels such as buttons, knobs, and touchscreens to convey their operational intentions, while the system's status is conveyed to them through displays, audio, and tactile information. Breitschaft et al. (2019) classified the provision of tactile feedback within the automotive interior into two categories based on its implementation from a technical perspective. These categories are active and passive feedback. Touchscreens' vibrotactile (active feedback) is often generated electrically by a built-in vibration actuator. Although there are other implementations of tactile feedback for touchscreens, such as piezoelectric (Wu and Smith, 2015), the vibration element is the more mature and commonly used. When the built-in vibration component receives a signal input, the vibration actuator performs the corresponding vibration effect to provide tactile feedback to the user. Physical buttons' feedback (passive feedback) can either be mechanically triggered or physically permanent. Automakers often use silicone rubber buttons due to their low cost and reliability. Valverde et al. (2019) demonstrated the deformation process of a silicone rubber button (cross-section) under an external force (Fig. 2), illustrating the force feedback perceived by the user. The buttons deform when subjected to user-applied pressure and make contact with the PCB (Printed Circuit Board) when they reach the sC position, which completes an information input. The silicone rubber will deform to its initial state (s1) when the pressure disappears.

Users may have different perceptual experiences when exposed to different modes of tactile feedback, which are perceived differently by sensory organs. Lederman and Klatzky (2009) described compliance in tactile interaction, which refers to the ability of a touched object to deform in response to force. In a simple one-dimensional model, compliance can be expressed by Hooke's Law as the relation of position to force. Tactile feedback of touchscreens and physical buttons are two typical forms, as touchscreens vibrotactile were designed to utilize the tactile illusion of compliance so that they would deliver a sense of displacement (Valverde et al., 2019), as opposed to physical buttons, which are subjected to external forces that produce a significant change in position. Srinivasan and LaMotte (1995) concluded that these two surface types have very different peripheral neural mechanisms. Moreover, the user's tactile perception of the touchscreen and physical button surfaces is also influenced by various factors, such as the spatiality of the skin's tactile perception. In summary, the mode and intensity of tactile feedback will change the finger's perception of compliance, spatiality, and other factors.

A biologically plausible structure supports the link between tactile perception and emotion. Touching a surface first stimulates mechanoreceptors and thermoreceptors beneath the skin (Lederman and Klatzky, 2009). The stimulation patterns are then mapped onto the outer areas of the brain. This initial processing relates to psycho-physical (or sensorial) judgments. In terms of a surface's tactile sensations, they include roughness, compliance, friction, and thermal properties (Klatzky et al., 2013). These judgments are then integrated and compared to memories in other brain areas, ultimately influencing our affective judgments (Kringelbach, 2005).

Based on these previous studies, the emotional impact of tactile feedback in in-vehicle interaction interfaces has been widely investigated. In touchscreen-based studies, Pitts et al. (2009) conducted simulated driving tests, revealing that tactile feedback can enhance drivers' emotional responses. Large et al. (2016) explored the effects of touchscreens and touchpads in automotive interface on drivers' subjective ratings (workload, emotional response, preferences) using four typical NDRTs, and showed that touchscreens were the most preferred/least demanding, and conversely, touchpads were the least preferred/least demanding. A more in-depth study (Large et al., 2019) comparing drivers from different cultural contexts (UK and China) showed that using a touchscreen as the primary control interface maximizes acceptance, and this study also revealed preference issues in different cultural markets.

As for the physical buttons, Wellings et al. (2010) evaluated the holistic experience of push-switches in luxury saloons by collecting hedonic, qualitative and semantic differential data, and results indicated that customers could distinguish between switches based on their level of liking for the perceived tactile qualities of the samples. Vieira et al. (2017) used Kensei engineering as a tool for assessing the subjective perception of in-vehicle rubber keypads, yielding better physical parameters for haptic feedback than using Snap Ratio, making it possible to provide valid correlations between perceptual vocabulary and the physical properties of in-vehicle keys. Gaspar et al. (2017) investigated the impact of hand exploration behaviour on subjective and emotional values in in-vehicle interaction interfaces, proposing a set of tactile engineering parameters for in-vehicle interface buttons based on user preferences, which helped manufacturers and their customers to better define interface requirements in relation to the subjective needs of users. Valverde et al. (2019) conducted an engineering-based study to investigate the quality of tactile feedback in automotive buttons for optimal and suboptimal interactions, contributing to a better understanding of button tactile feedback and meeting brand sensory expectations during the early stages of HMI design.

The above studies have established a correlation between tactile feedback in automotive interfaces and drivers' emotions, resulting in several automotive tactile feedback parameters and evaluation methods. However, it is unknown how the connection between the automotive touchscreen and the physical buttons and their intensities affects the driver's emotions.

On the other hand, Pitts et al. (2012b) reported that drivers' perception of tactile feedback in in-vehicle central control interfaces is influenced by their cognitive load; drivers exhibit decreased tactile sensitivity in distracted states, where tactile feedback may not be sufficient to provide operational confirmation (Pitts et al., 2012b; Leung et al., 2007). Moreover, the complexity of drivers' tasks may influence their ability to perceive tactile stimuli (Tang et al., 2023). Considering that task difficulty is considered a critical factor affecting driver interaction with in-vehicle infotainment systems (Ban and Park, 2024; Jakus et al., 2015; Sterkenburg and Jeon, 2020), further exploration is needed to investigate whether the impact of TFM and TFI is subject to modulation by non-driving related task difficulty (NTD) levels.

1.2. Interaction feedback and emotions

Interaction feedback is a critical component of HMI, providing users with information regarding the outcome of their operations and the system's status (Donmez et al., 2007; Gaffary and Lécuyer, 2018). "The Gulf of Evaluation" (Norman, 2013, pp.38-40) describes the effort required by users to obtain feedback, which suggests that clear, understandable feedback is important for users in driving environments where the driving task is cognitively and visually demanding. Breitschaft et al. (2019) divided tactile processing into several stages, each with corresponding psychological expectations, which are altered by the tactile feedback provided by the HMI at different stages. As for users, positive feedback typically yields positive effects, such as feelings of pleasure and satisfaction. On the contrary, negative feedback can have adverse effects, potentially eliciting emotions like anger, tension, or sadness (Sargeant et al., 2008). Emotions have long been considered crucial factors influencing driver decision-making and attention (Zhou et al., 2022; Huo et al., 2023). Positive emotions like pleasure and confidence enhance the driving experience and road safety. In contrast, negative emotions like anger and frustration can lead to aggressive driving behaviour, driver distraction, increased hazard perception, and an increased risk of road safety incidents (Chan and Singhal, 2015; Sterkenburg and Jeon, 2020).

Our objective is to investigate the emotional states of drivers when exposed to different modes and intensities of tactile feedback in in-vehicle central control interfaces. Measuring subjective emotions evoked by tactile feedback from in-vehicle central control interfaces is critical. Researchers have used two main perspectives of subjective emotion measurement instruments: a dimensional or discrete frame (Mauss and Robinson, 2009). Views from a dimensional perspective suggest that emotional states are organized by fundamental factors such as valence, arousal, and dominance. Conversely, the view from discrete emotions suggests that each specific emotion, such as anger, sadness, and happiness, has unique experiential, physiological, and behavioural correlates (Barrett, 1998; Khare et al., 2024). Although there are much more discussion around dimensional and discrete perspectives, some research suggests that driving behaviours and performance are affected by a combination of influences from emotional valence, arousal, and dominance (Chan and Singhal, 2015; Zimasa et al., 2019), which means that dimensional frames better capture this measure of drivers' emotion relative to discrete frames.

In this study, we employed the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994). This dimensional assessment technique evaluates the valence (1 for extremely pleasant and 9 for extremely unpleasant), arousal (1 for extremely calm and 9 for extremely aroused), and dominance (1 for totally controlled and 9 for totally in control) in relation to an individual's subjective emotional reaction to a wide range of stimuli. Different valence, arousal, and dominance combinations are used to describe emotional state, and they almost explain all reliable differences in existing emotional state measurements (Russell, 1979; Falender and Mehrabian, 1980). For instance, anger is characterized by unpleasantness, high arousal, and dominance, while anxiety is marked by unpleasantness, excitement, and obedience. SAM has been validated in related studies to measuring emotion, such as driving performance (Steinhauser et al., 2018; Zhang et al., 2023), automotive HMI (Large et al., 2016, 2019) and interaction feedback (Swindells et al., 2007; Rhiu et al., 2018). Although there are many other classical subjective emotion assessment techniques, such as positive and negative affect schedule (PANAS) (Gellman and Turner, 2013), photographic affect meter (PAM) (Pollak et al., 2011) and experience sampling method (ESM) (Kang et al., 2022). Combining the characteristics of SAM and previous studies, it is more appropriate to use SAM to measure subjective emotions in this study. In addition to measuring emotional states, NDRT performance (efficiency and accuracy) was used to assess the relationship between interface task performance and driver emotional states. We propose the following four hypotheses.

[H1.]. Tactile feedback on touchscreens elicits more positive emotional states in drivers.

[H2.]. Higher intensity in-vehicle central control interface tactile feedback does not always evoke more positive emotional in drivers.

[H3.]. NDRT difficulty alters drivers' ability to perceive feedback and therefore further affects their emotional state.

[H4.]. With the enhancement of tactile feedback, the operation efficiency and accuracy of in-vehicle central control interfaces are expected to be improved.

2. Methods

2.1. Experimental variable settings

We used a 2 × 3 × 2 within-subject design. All participants experienced all 12 trials, with TFMs (e.g. force feedback from physical buttons, vibration feedback from the touchscreen), TFIs (e.g. high, medium, low), and the NTDs (e.g. simple, complex) serving as independent variables (Table 1), and the order was counterbalanced. There are still some setup issues that need to be clarified.

Table 1
Details of the independent variables.

TFM (2)	TFI (3)	NTD (2)
Touchscreen vibration feedback	High	Simple
Physical button force feedback	Medium	Complex
	Low	

2.1.1. TFM settings

Two types of tactile feedback were examined: vibration feedback for touchscreens and force feedback for physical buttons. For the touchscreen's tactile feedback setup, we used an iPad Pro (10.5-inch, with resolution 2224 × 1668) as the display panel and fixed a responsive vibration actuator in the middle of its back. It was placed as a unit on a stand, and a pressure sensor (FSR) was set up at the point of contact with the stand. When the FSR senses the pressure from the user's press, it outputs a signal to the Arduino board connected to it. Then the PCB transmits wireless data to the vibration actuator (Fig. 1). The design of the physical buttons in this experiment referenced the internal structure commonly used by automakers, detailed instructions are in Section 1.1. This typical push button deforms due to the input of an external force, and the subsequent rebound provides the user with corresponding force feedback (Fig. 2). All physical buttons are fixed on an 18 × 25 × 5 cm hard case.

It is important to note that the sensation of buttons involves various variables such as surface friction, stickiness, temperature, and finger compliance (Lederman and Klatzky, 2009). To ensure consistency in the study's direction, we selected physical buttons and touchscreens with similar surface sensations, and participants were instructed to focus on the intensity of touchscreen vibrations and physical button force feedback throughout both preliminary and formal evaluations.

2.1.2. TFI settings

We obtained representative tactile feedback intensities through experts' classification in a preliminary user experiment. Based on previous studies of tactile feedback intensity settings for physical buttons (Gaspar et al., 2017; Ban et al., 2013; Miyairi et al., 2022), eleven different intensities of force feedback for physical buttons, with values corresponding to 2 N–7N (0.5 N interval per condition). The perception of vibrotactile feedback on touchscreens mainly consists of frequency, waveform and duration. The frequency directly affects the intensity of the vibration, so we uniformly use a sine wave sustained for 150ms without inducing any delayed responses (Dabic et al., 2013; Diwischek and Lisseman, 2015; Park et al., 2011). Eleven different vibration feedback for touchscreens, with values corresponding to 50 Hz–250 Hz (20 Hz interval per condition), were presented to seven expert users counterbalanced; expert users can click freely to experience their intensities. Afterwards, a 7-point Likert scale (1 for low intensity and 7 for high intensity) was used to rate the feedback intensity perception of each physical button and touchscreen feedback. Samples of tactile feedback with representative high, medium, and low intensities for physical buttons and touchscreens were selected as the formal experimental materials for this study (Table 2). The results are consistent with the "Just Notable Differences" (JND) of 30% in the frequency of vibration feedback (Diwischek and Lisseman, 2015).

2.1.3. NDRT settings

In order to simulate real-world usage of the in-vehicle central control interface and to avoid selecting tasks that require the user to swipe or use knobs to operate, this would introduce inconsistencies in the input methods. Two typical NDRTs were selected for study, i.e., the music playback task and the temperature adjustment task (Maciej and Vollrath, 2009), corresponding to the simple and complex tasks designed in the experiments.

The settings of NDRTs' difficulty based on the NDTR operating locations (i.e.operation of the lower part of the HMI corresponds to more

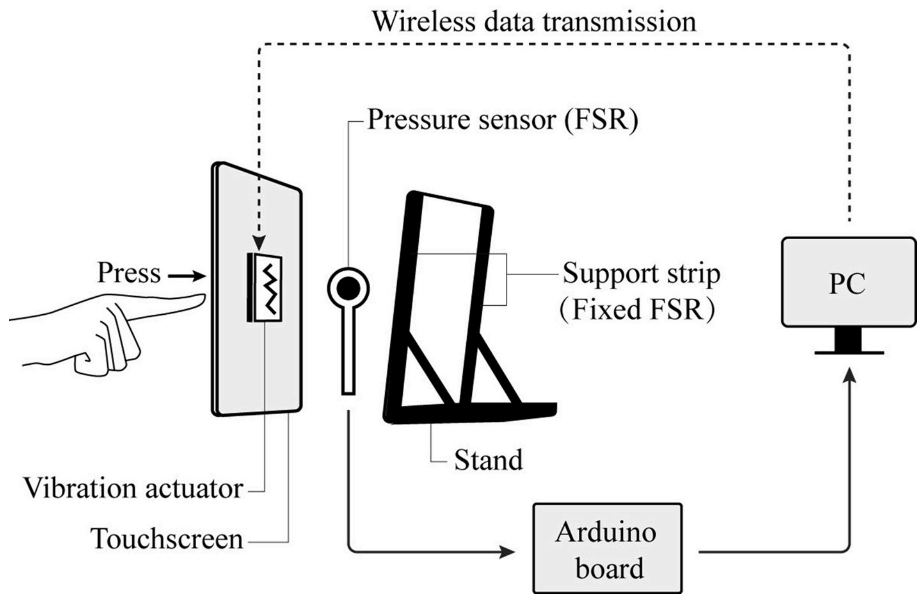

Fig. 1. The rationale of touchscreen tactile feedback.

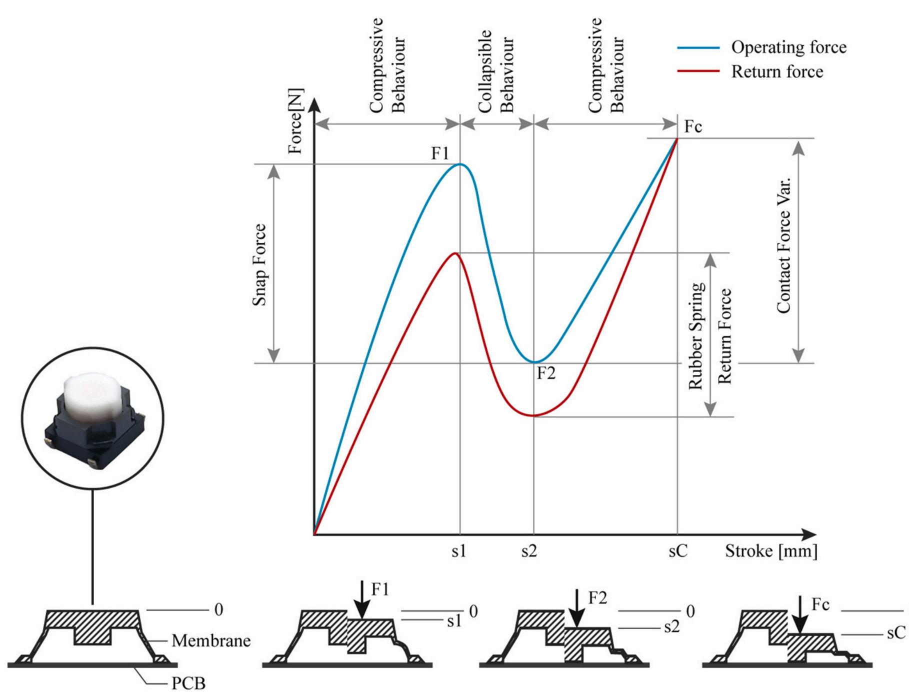

Fig. 2. The rationale of physical button force feedback. A typical physical push-button (left); Cross section for force-deformation processes (bottom); Force-stroke curve (right).

Table 2
Corresponding parameters of TFIs for touchscreen vibration force feedback and physical button force feedback.

TFI	Vibration parameters	Force parameters
High	250 Hz	7 N
Medium	150 Hz	4.5 N
Low	50 Hz	2 N

difficulty) (Ban and Park, 2024), physical activity required (i.e. number of steps) (Jakus et al., 2015), and the cognitive workload required to complete the tasks. Thus, the music playback (Simple) task is designed to be in the upper half of the HMI and consists of three easy-to-understand steps (Table.3a), which corresponds to the temperature adjustment (Complex) task in the lower half and consists of seven none-logical steps (Table.3b). Participants were required to complete the corresponding NDRTs through a specific sequence of operations.

2.2. Participants

Forty-two participants (25 females and 17 males) from Ningbo University participated in the study through a simulator participant pool and campus postings, with a mean age of 24.76 years (SD = 4.46) and driving experience of 3.17 years (SD = 2.93). The selection criteria were possession of a valid driving licence and normal or corrected-to-normal vision. Considering that the experiment required using the right hand for

Table 3a
Instruction for music playback (simple) task.

Step	Icons to click	Specific actions required
1		Play music
2		Setting music to play randomly
3		Play the next piece of music

Table 3b
Instruction for temperature adjustment (complex) task.

Step	Icons to click	Specific actions required
1		Turn on the air conditioning in the car
2		Set the air conditioning mode to “AUTO"
3		Switch on the heated driver’s seat
4		Switch on the front window defogging function
5		Set to blow air from below
6		Switch on the internal air circulation of the vehicle
7		Switch on the rear window defogging function

HMI manipulation tasks, the participants screened were all right-handed, did not have severe tactile perception deficits, and had experience operating touchscreens and physical buttons. All participants were given 20 RMB after completion of the experiment. This research complied with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and received the ethical approval from Ethical Review Committee, Ningbo University.

2.3. Apparatus and materials

The experiment was conducted in a laboratory using a medium-fidelity simulator with a 65-inch display (with resolution 3840 × 2160), a high-performance computer, a steering wheel, a brake, an accelerator pedal and a seat. The driving simulation scenario was constructed using City Car Driving. It featured a 5-km-long three-lane city road with a traffic density of approximately 15 vehicles/km per hour in each direction (Fig. 3).

The in-vehicle central control panels used in the experiments (both touchscreen interface and physical button interface) were replaceable, so they were all placed in the same position on the right side of the steering wheel as the in-vehicle central control interface of the real vehicle. In addition, a video camera was fixed at the right rear position of the participant to record the participant’s behavioural performance. The layout of the experimental environment and equipment is shown in Fig. 3.

Visual characteristics were controlled based on previous studies (Kim et al., 2014; Tao et al., 2018). The interface colours and visual feedback for physical buttons and touchscreens were standardized. The interaction interface had a black background, square black buttons (20 × 20 mm), and a white border. When a button was pressed, it turned white until the task was reset, and physical buttons activated a white light at the bottom when pressed. Since touchscreen vibration motors and mechanical buttons generate noise when drivers operate, participants wore noise-cancelling headphones to isolate the noise to prevent cross-modal effects (Lederman and Klatzky, 2009). The study was conducted in a closed and quiet university laboratory; for this purpose, the headphones simulated various noises in the driving environment.

2.4. Procedures

After participants provided informed consent, they were asked to complete a prequestionnaire asking for their demographic information. Participants could adjust the chair according to their preferences to accommodate the experimental condition. Following this, participants have approximately 3 min to familiarize themselves with the driving simulator. Considering that this study aimed to explore the impact of tactile feedback from physical buttons and touchscreens on driver emotional states rather than assessing system usability, participants were allowed to freely explore the in-vehicle infotainment system provided in the practice session and were required to master the set music playback and temperature adjustment tasks during this practice.

In the formal experiment, participants completed the specified NDRTs within the simulated driving scenario. The simulated vehicles maintained a steady speed of 60 km/h in the middle lane, participants were asked to remain aware of road conditions and were given digitally generated voice prompts every 2 min, instructing them to operate the in-vehicle HMI interface to perform the corresponding NDRT. For the fluency of the experiment, the stimuli were divided into two groups based on the TFM. Each participant was required to complete both sets of stimuli in a randomized order. The conditions under which participants were tested are shown in Fig. 4, and the detailed stimulus descriptions are shown in Fig. 5 (right). After each trial, participants were required to fill out post-driving Self-Assessment Manikin surveys to measure their subjective emotions. Objective data concerning the performance of NDRTs were collected through behavioural observation. The driver’s behaviour was recorded through 60 fps high-definition video recording equipment. The time from the end of the voice prompts to the completion of the NDRT and the number of incorrect actions was used to analyze the efficiency and accuracy of in-vehicle central control interface operations.

2.5. Statistical analysis

This study used a within-subject design to compare the effects of the TFM (touchscreen vibration feedback vs Physical button force feedback), the TFI (high vs medium vs low), and the NTD (simple vs complex) on drivers’ subjective emotion. In order to test the hypotheses regarding whether there was a significant effect between TFMs, TFIs as well as NTDs and to what extent, three subfactors of SAM (valence, arousal, and dominance) were each analyzed using a separate repeated measures analysis of variance (RM-ANOVA). In the preprocessing step, subjective emotion ratings were obtained using the corresponding 9-point Likert scale values for each emotional dimension. One set of outliers was detected and replaced with mean values. Objective performance data were tallied from behavioural observation recordings, with each driver’s completion time and error rate being recorded for each of the 12 conditions.

RM-ANOVA in this study requires examining three basic assumptions

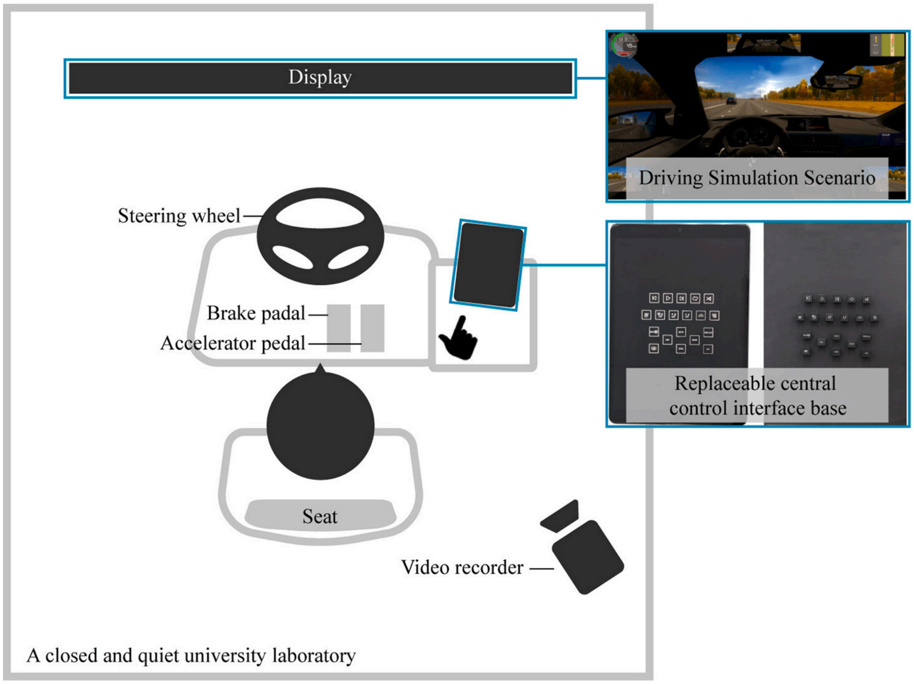

Fig. 3. Experimental environment, equipment description and layout.

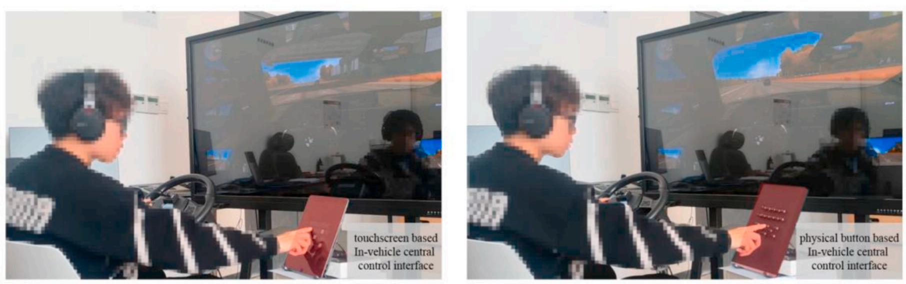

Fig. 4. Conditions under which participants were tested.

of parametric statistical tests: interval-scale data of the dependent variable, normality, and sphericity (Gamst et al., 2008; McCrum-Gardner, 2008). Firstly, our study used SAM (a 9-point Likert scale) for emotion ratings, which measures at the ordinal level. There is a common agreement that parametric statistical techniques are robust to this assumption violation, and thus, the use of parametric techniques to analyze SAM ratings can be justified (Norman, 2010). Secondly, by means of the graphical methods (Stem-and-Leaf displays and Q-Q plots), the results were normally distributed overall (Mishra et al., 2019). Thirdly, Mauchly's test was conducted, and the sphericity assumptions were met ($p > 0.05$). Therefore, the three-way RM-ANOVA was deemed appropriate.

To ascertain the impact of independent variables on the performance of central control interface operation, we employed RM-ANOVA as well and conducted correlation analyses to test the relationship between drivers' subjective emotions and operation performance. All participant data were analyzed using SPSS 27.0 data analysis software, with a significance level set at $\alpha = 0.05$ (two-tailed). Confidence intervals (CIs) were set at a 95% level. When main effects or interactions were significant, Bonferroni post-hoc comparisons were conducted. If Mauchly's sphericity test probability was <0.05, Greenhouse-Geisser corrections were applied.

3. Results

3.1. SAM subjective emotion questionnaire

Based on SAM ratings, Cronbach's alpha was calculated, yielding satisfactory internal consistency (Table 4). Therefore, the effect of tactile feedback from the in-vehicle central control interface on drivers' emotions can be described using valence, arousal, and dominance. Table 5 presents the means and standard deviations of the valence, arousal and dominance ratings on the SAM.

3.1.1. Effect of TFM on emotion

The RM-ANOVA revealed a significant effect of TFM on emotional valence $F_{(1,41)} = 10.96$, $p = 0.002$, $\eta_p^2 = 0.21$, and dominance $F_{(1,41)} = 11.53$, $p = 0.002$, $\eta_p^2 = 0.22$ (Table 6). Touchscreen tactile feedback induced higher emotional valence ratings (+1.16) and lower emotional dominance ratings (−0.49) from drivers than physical buttons.

3.1.2. Effect of TFI on emotion

The RM-ANOVA showed that TFI significantly affected driver emotional valence $F_{(2,40)} = 4.63$, $p = 0.015$, $\eta_p^2 = 0.19$, and emotional arousal $F_{(2,40)} = 10.13$, $p < 0.001$, $\eta_p^2 = 0.23$. The ratings of emotional valence increased with enhanced intensity, and the ratings of emotional arousal showed the same trend (Fig. 7). The above results indicate that

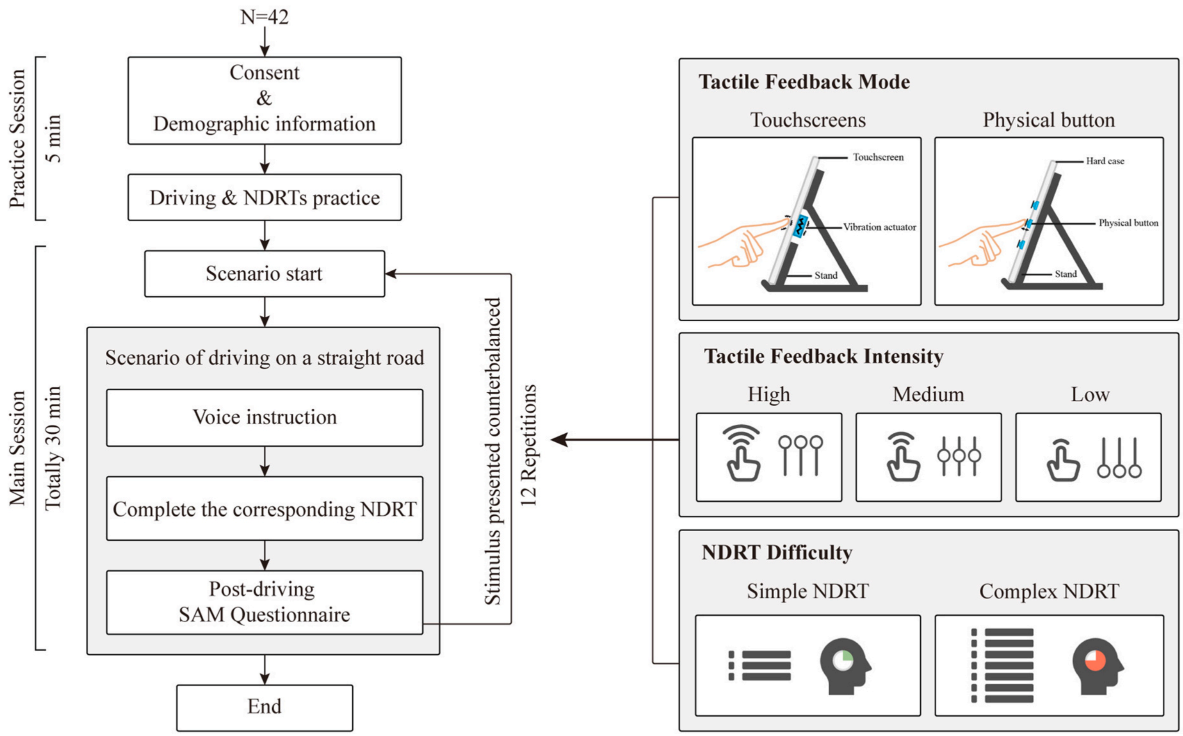

Fig. 5. Flowchart of the experimental procedure (left) and stimulus of the experiment (right).

Table 4
Cronbach's α coefficients of measures.

Measures	α
Valence in SAM	0.76
Arousal in SAM	0.90
Dominance in SAM	0.94

with the enhancement of vibration feedback, the level of driver emotional valence increased, and so did the emotional arousal.

3.1.3. Effect of NTD on emotion

The RM-ANOVA revealed that the NTD significantly affected emotional valence $F_{(1,41)} = 78.82, p < 0.001, \eta_p^2 = 0.658$, and emotional arousal $F_{(1,41)} = 9.57$, $p = 0.004$, $\eta_p^2 = 0.189$. Lower NTD reduced drivers' emotional valence levels and resulted in higher arousal.

3.1.4. Effect of TFM and TFI on emotion

There was a significant interaction effect between TFM and TFI on emotional valence $F_{(1.75,\ 14.44)} = 4.90, p = 0.013, \eta_p^2 = 0.11$, and arousal $F_{(2,40)} = 14.57, p < 0.001, \eta_p^2 = 0.42$. Simple effect analysis revealed that high-intensity touchscreen tactile feedback had the highest valence ratings (M = 6.10, SD = 1.95) (Fig. 8a), which were significantly higher than low intensity (CI [0.476, 1.834], $p = 0.001$) and showed no significant difference from medium intensity. For emotional arousal, high-intensity touchscreen tactile feedback had the highest arousal ratings (M = 5.02, SD = 2.55) (Fig. 8b), which were significantly higher than medium intensity (CI [0.23, 1.13], $p = 0.004$) and low intensity (CI [1.29, 2.66], $p < 0.001$). Furthermore, there were no significant pairwise comparisons for emotional valence and arousal ratings of physical button tactile feedback.

3.1.5. Effect of TFM, TFI and NTD on emotion

There was a three-way interaction between TFM, TFI, and NTD: emotional valence $F_{(2,40)} = 3.25, p = 0.49, \eta_p^2 = 0.14$, dominance $F_{(2,40)} = 3.37, p = 0.44, \eta_p^2 = 0.14$. Simple effect analysis of emotional valence ratings revealed that when the highest intensity of touchscreen tactile feedback was provided, completing the simple NDRT and complex NDRT exhibited higher subjective ratings than physical button tactile feedback validity ratings when performing simple NDRT (CI [0.50,2.07], $p = 0.002$) or complex NDRT (CI [0.47,2.06], $p = 0.003$) (Fig. 9). However, when providing medium-intensity tactile feedback to perform complex NDRTs, touchscreen tactile feedback had a higher valence ratings (+1.28) than physical button tactile feedback (CI [0.60,1.97], $p < 0.001$), a trend that did not occur when performing a simple NDRT. In addition, when low intensity tactile feedback was

Table 5
Means and standard deviations for subjective emotion rating measures (**Note*: H, high intensity; M, medium intensity; L, low intensity).

		Simple NDRT						Complex NDRT					
		Touchscreen			Physical button			Touchscreen			Physical button		
		L	M	H	L	M	H	L	M	H	L	M	H
Valence	M	5.36	6.19	6.69	5.24	6.07	5.40	4.52	5.38	5.50	4.29	4.10	4.24
	SD	2.10	1.74	1.99	2.10	1.69	1.75	1.85	1.78	1.90	1.93	1.79	2.17
Arousal	M	2.81	3.86	4.86	4.33	4.31	4.02	3.29	4.83	5.19	4.43	4.55	4.86
	SD	2.06	2.36	2.61	2.40	2.21	2.21	1.98	2.36	2.49	2.10	2.07	2.29
Dominance	M	2.48	2.98	3.36	3.81	3.62	3.43	3.07	3.48	3.38	3.55	3.69	3.76
	SD	1.94	2.03	2.54	2.39	2.36	2.12	2.05	2.14	2.40	2.39	2.35	2.36

Table 6
RM-ANOVA results for main and interaction effects for emotion valence, arousal and dominance.

	Variables	df	F	p value	significance	η_p^2
Valence	TFM	1	10.96	0.002**	Y	0.211
	TFI	2	4.63	0.015*	Y	0.188
	NTD	1	78.82	0.000***	Y	0.658
	TFM x TFI[a]	1.75	4.90	0.013*	Y	0.107
	TFM x NTD	1	1.27	0.267	N	0.030
	TFI x NTD	2	1.88	0.166	N	0.086
	TFM x TFI x NTD	2	3.25	0.049*	Y	0.140
Arousal	TFM	1	1.86	0.180	N	0.043
	TFI[a]	1.65	11.89	0.000***	Y	0.225
	NTD	1	9.57	0.004**	Y	0.189
	TFM x TFI	2	14.57	0.000***	Y	0.422
	TFM x NTD	1	0.41	0.524	N	0.010
	TFI x NTD	2	0.76	0.474	N	0.037
	TFM x TFI x NTD	2	1.89	0.165	N	0.086
Dominance	TFM	1	11.53	0.002**	Y	0.220
	TFI[a]	1.78	1.03	0.356	N	0.037
	NTD	1	1.90	0.176	N	0.044
	TFM x TFI	2	1.29	0.287	N	0.061
	TFM x NTD	1	0.90	0.349	N	0.021
	TFI x NTD	2	0.19	0.829	N	0.009
	TFM x TFI x NTD	2	3.37	0.044*	Y	0.144

*p < 0.05.**p < 0.01.***p < 0.001.
[a] Greenhouse-Geisser correction was used wherever the assumptions of sphericity were violated.

provided, neither touchscreen tactile feedback nor physical buttons were significant in the simple effects analysis.

In the case of simple NDRT, the lowest-intensity touchscreen tactile feedback had the lowest valence ratings (Fig. 6a), which was lower than medium intensity (CI [−1.37, −0.30], $p = 0.003$) and high intensity (CI [−2.01, −0.66], $p < 0.001$). However, high-intensity feedback had only a slight difference from medium intensity (+0.12). The same trend was observed when operating complex NDRT, with the lowest-intensity touchscreen tactile feedback having the lowest valence ratings, which were lower than medium-intensity (CI [−1.56, −0.16], $p = 0.018$) and high-intensity (CI [−1.78, −0.17], $p = 0.019$). In the case of physical button tactile feedback, in simple NDRT, medium-intensity feedback resulted in the highest valence ratings, which was higher than low-intensity feedback (CI [0.18, 1.49], $p = 0.014$) and high-intensity feedback (CI [0.14, 1.19], $p = 0.014$) (Fig. 9). When performing complex NDRT, there were no significant pairwise comparisons for valence ratings affected by intensity factors. Additionally, simple NDRTs received higher valence ratings in all conditions.

In terms of the dominance dimension, providing low-intensity touchscreen tactile feedback to complete complex NDRT led to a higher (+0.60) level of emotional dominance. This trend was also observed at medium intensity (+0.50). When executing simple NDRT, the emotional dominance level induced by low-intensity physical button tactile feedback was higher than low-intensity touchscreen tactile feedback (CI [0.62, 2.05], $p < 0.001$) (Fig. 9). The same trend was observed with medium-intensity physical button tactile feedback's emotional dominance ratings, which were higher than medium-intensity touchscreen tactile feedback (CI [0.15, 1.13], $p = 0.011$). While completing simple NDRT, the highest intensity of touchscreen tactile feedback resulted in a higher level of emotional dominance, which was higher than the weakest touchscreen tactile feedback (CI [0.69, 1.69], $p = 0.034$).

3.2. *Non-driving related task performance*

Table 7 displays the average task completion times and error rate for each tactile feedback condition during NDRTs. Results from a RM-ANOVA showed that the average task completion time was affected by the TFM (p = 0.014) and NTD (p < 0.001). However, there was no significant impact of TFI on task completion time (p = 0.336). Furthermore, an interaction effect was observed between TFM and TFI (p = 0.006). Regarding the average error rate, a RM-ANOVA revealed a significant main effect of TFM (p = 0.038). In contrast, no significant main effect of TFI (p = 0.532) was observed. However, there was an interaction effect between TFM and TFI (p < 0.001), as well as an interaction effect between TFM and NTD (p = 0.017). Correlation analysis between operational performance on NDRTs and different dimensions of drivers' emotional state is shown in Table 8.

4. Discussion

The main purpose of this study is to investigate how tactile feedback on in-vehicle HMI interfaces affects driver emotions. Forty-two participants experienced 12 stimuli and completed a SAM questionnaire to assess their emotional states after each stimulus. The results of our research show that the emotional state of drivers is significantly influenced by the TFM and TFI, as well as the NTDs. However, the impact of different TFMs, TFIs, and NTD levels varies.

Our study reveals that the TFMs (touchscreen tactile feedback and physical button tactile feedback) significantly affects the emotional states of drivers, particularly in terms of valence and dominance. The touchscreen interface evokes higher valence ratings (+0.75) and lower

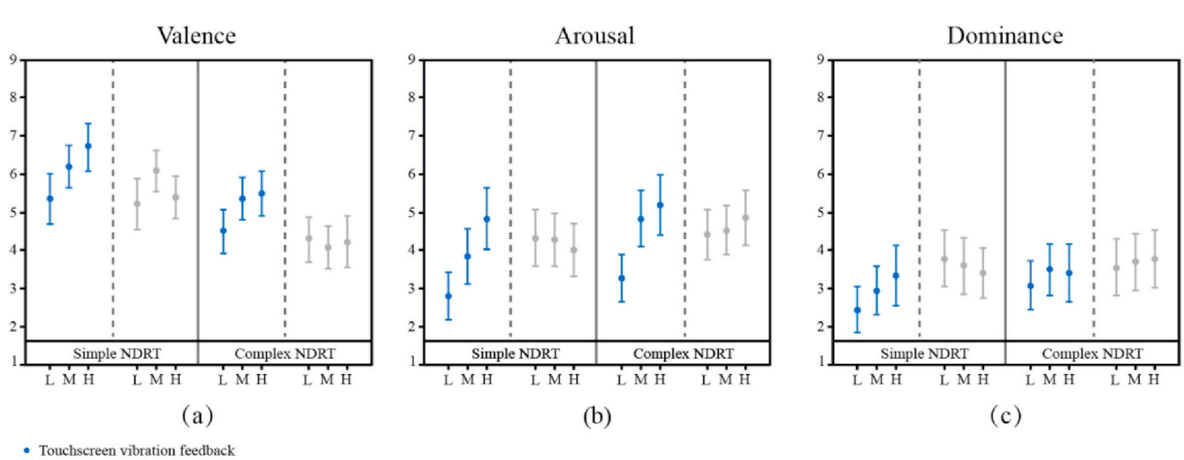

Fig. 6. Effect of TFM, TFI and NTD on drivers' emotion.
(Error bars indicate 95% confidence interval for the mean).

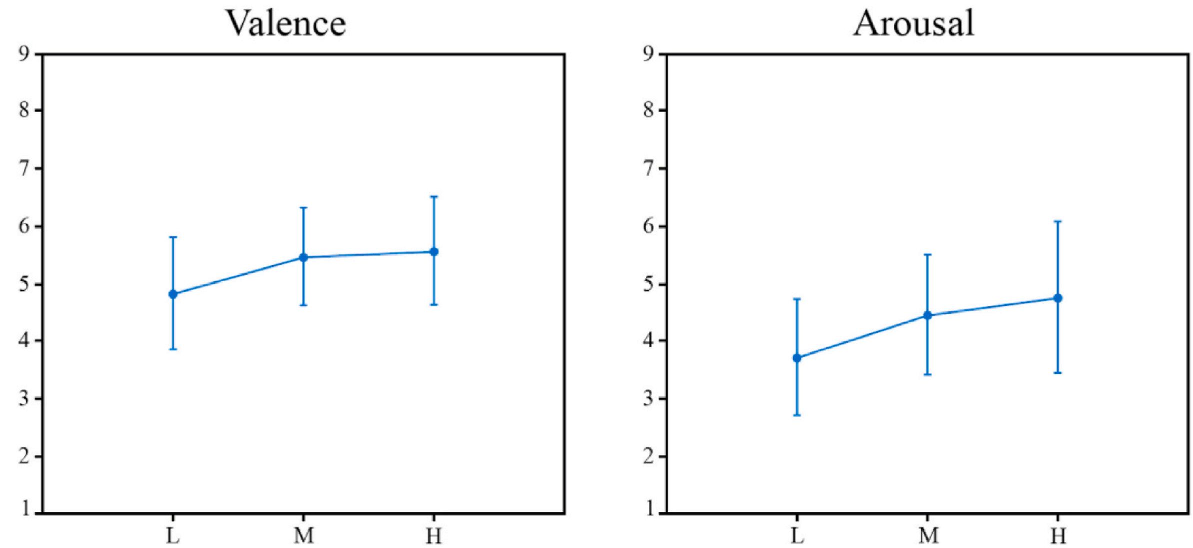

Fig. 7. Effect of TFI on drivers' emotional valence and arousal (Error bars indicate 95% confidence interval for the mean).

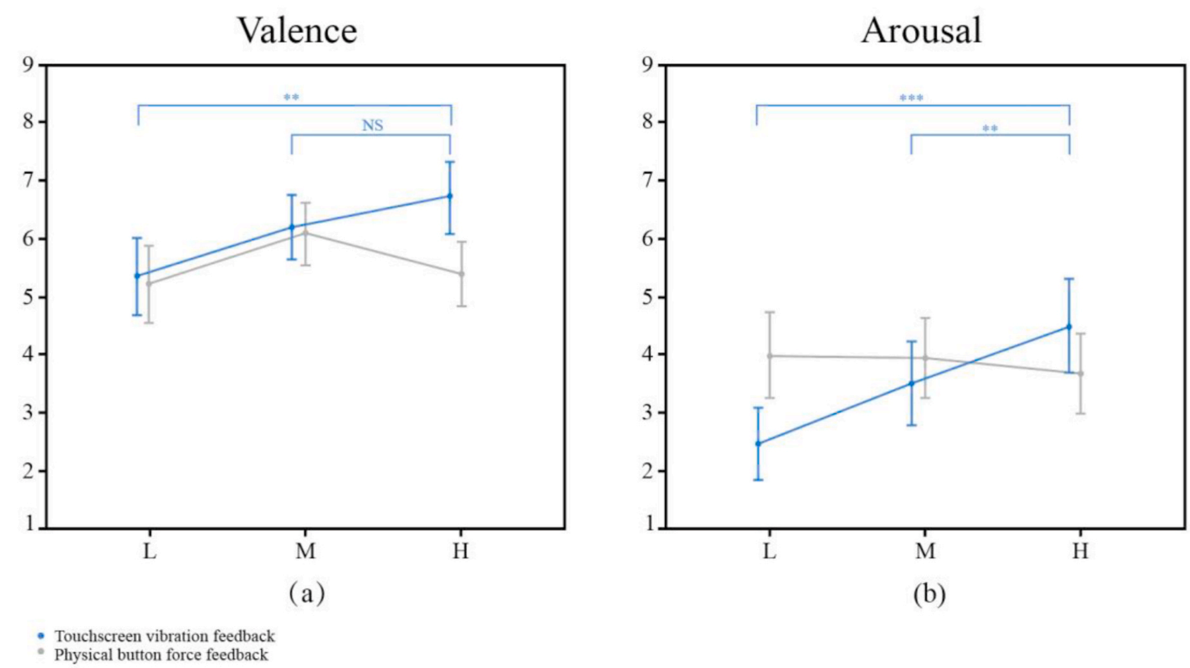

Fig. 8. Effect of TFM and TFI on drivers' emotional valence (a) and arousal (b) (Error bars indicate 95% confidence interval for the mean).

dominance ratings (−0.52) than physical buttons. A three-dimensional-based model of emotion (Khare et al., 2024) (Fig. 10) suggests that when drivers are initially in a neutral emotional state, higher valence and lower dominance tend to satisfy them. Consequently, touchscreen tactile feedback positively impacts drivers' emotional states, supporting hypothesis 1. This result is consistent with prior research findings (Pitts et al., 2012b; Large et al., 2019). Previous studies attribute this result to the touchscreen's unified input and output device, which does not require users to shift their visual attention during interactions, making touchscreen interfaces significantly preferred (Chung et al., 2010). It is worth noting that using a touchscreen to perform NDRT aggravates the driver's visual workload (Deng and Kaber, 2022), suggesting that the complexities of specific driving environments may still attenuate the improvements brought about by touchscreens for the driver's subjective emotions and that the real emotional response may be more significant.

Regarding tactile feedback intensity, higher-intensity touchscreen tactile feedback triggers stronger emotional responses in drivers, with a positive correlation between intensity and driver emotional reactions. However, this trend is not observed in physical buttons (Fig. 8a). Notably, significant interaction effects between tactile feedback characteristics were detected. Through simple effect analysis, the highest intensity physical button tactile feedback leads to decreased emotional valence ratings when performing simple NDRTs. Simultaneously, the emotional valence ratings for the highest intensity touchscreen tactile feedback exhibit a minor difference compared to moderate intensity. This result suggests that the increase in the intensity of tactile feedback does not continuously optimize the driver's emotional experience, aligning with hypothesis 2. Studies based on perceptual usability and cognitive load (Dunn et al., 2021) suggest that overly strong feedback can cause user distress. Stronger feedback optimizes user efficiency and

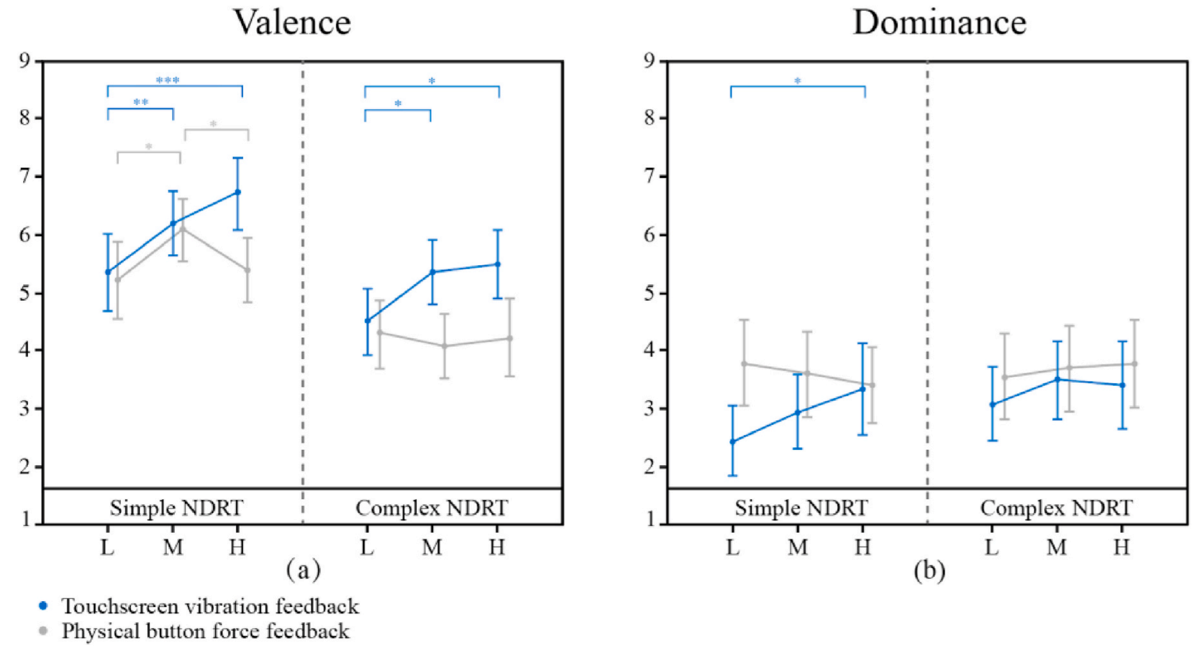

Fig. 9. Effect of TFM, TFI and NTD on emotional valence (left) and dominance (right) (Error bars indicate 95% confidence interval for the mean).

Table 7
Means and standard deviations for NDRT performance. (*Note: H, high intensity; M, medium intensity; L, low intensity).

		Simple NDRT						Complex NDRT					
		Touchscreen			Physical button			Touchscreen			Physical button		
		L	M	H	L	M	H	L	M	H	L	M	H
Completion time (s)	M	4.68	4.93	4.79	5.62	5.24	5.76	9.47	10.34	9.63	10.08	10.16	10.55
	SD	1.56	1.60	1.33	1.82	1.42	2.08	3.57	3.92	4.27	4.36	3.51	3.38
Error rate	M	0.21	0.29	0.24	0.21	0.19	0.29	0.67	0.64	0.76	0.33	0.33	0.40
	SD	0.52	0.64	0.62	0.65	0.59	0.67	0.85	0.88	1.03	0.72	0.65	0.66

Table 8
Correlation analysis between operational performance on NDRTs and different dimensions of drivers' emotional state.

	Valence	Arousal	Dominance	Completion time	Error rate
Valence	1	0.085	−0.166**	−0.306**	−0.078
Arousal		1	0.534**	0.048	0.040
Dominance			1	−0.027	−0.006
Completion time				1	0.371**
Error rate					1

**At level 0.01 (two-tailed), the correlation was significant.

task difficulty when completing complex tasks, as corroborated by data in Section 3.2 regarding task performance. However, drivers only require a little attention during relatively simple NDRTs. Excessive intensity in physical button tactile feedback makes the feedback information overly complex. Vehicle driving tasks are of high complexity, and drivers need to respond instantly to dynamic changes in road, vehicle and pedestrian factors, which places high demands on the driver's cognitive load visual detection and other dimensions (Zhang et al., 2023; Suh and Ferris, 2019; Zimasa et al., 2019). Excessive intensity in physical button tactile feedback makes the feedback information overly complex. This will be perceived by the driver as redundant information, which reduces the perceived usability of the button and leads to lower emotional value ratings. On the other hand, participants' perceptual compliance in performing actions varied, with high-intensity tactile feedback on physical buttons requiring the user to exert greater effort themselves. Norman (2013, pp. 38–40) explains the effort that users have to put in to get feedback. In the present study, the decrease in emotional valence is explained when the user exerts too much effort to complete the desired task. In summary, within the normal usage range, higher-intensity touchscreen tactile feedback can induce a more positive emotional experience for users. In contrast, excessively high-intensity physical button tactile feedback has a significant adverse impact on driver emotional states.

Additionally, the study found that physical buttons exhibited deficiencies in accomplishing complex NDRTs. Drivers' emotional valence ratings remain relatively low, and an increased intensity does not correspondingly improve driver emotions. This result validates the viewpoints put forth by Leung et al. (2007) and Pitts et al. (2012a): increased cognitive load diminishes participants' sensitivity to tactile stimuli, and the complexity of NDRTs can affect drivers' tactile sensitivity, which partially supports Hypothesis 3. Unlike physical button feedback, touchscreen feedback did not display a similar attenuation of tactile sensitivity. This divergence may be attributed to differences in human physiological sensory organs. While vibrations are directly perceived, the forces in press feedback undergo more complex processing through human sensory organs (Lederman and Klatzky, 1987, 2009). The tactile subsystem utilizes sensors on the skin to perceive pressure, vibrations, and temperature. In contrast, the kinesthetic subsystem relies on sensors on muscles, tendons, and joints to perceive force, position, and motion information. The human body uses motion subsystems related to hand movement patterns or exploration processes to process sensory data and extract information about object properties. Overall, although the hypotheses were partially supported, the affective

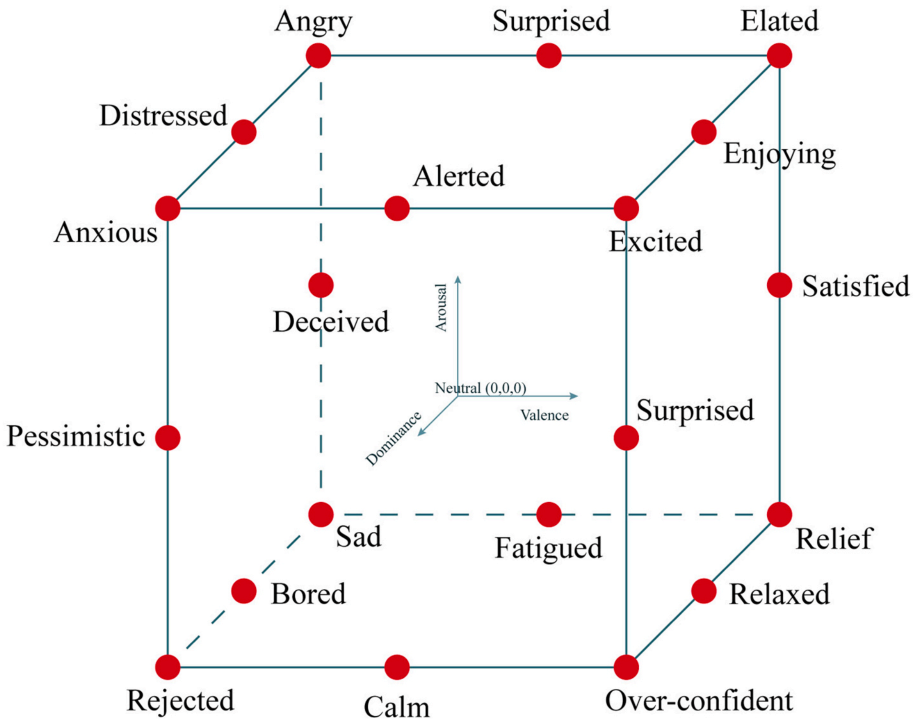

Fig. 10. A three-dimensional model of emotions.

relationship in Hypothesis 3 was not directly supported by the data on driver's perceived tactile intensity. For drivers, a complex influence relationship exists between cognitive load and emotion (Sugimoto et al., 2020; Zimasa et al., 2019). Many external factors might impact the results, such as different finger compliance and JND between each individual (Valverde et al., 2019; Diwischek and Lisseman, 2015), previous experience with HMI operation, driving style and NDRT operating habits. Therefore, further research is still needed to reveal how cognitive load affects drivers' tactile perceptual abilities and how this altered tactile perception may further affect drivers' emotions.

Based on the operational efficiency and accuracy of the automotive central control interface, the touchscreen demonstrates superior and more stable operational efficiency and accuracy (Table 6), supporting hypothesis 4. In conclusion, the result provides support for the advantage of touchscreen interfaces over physical buttons within a driving context from the perspective of emotion experiences and operational stability.

Fig. 11 illustrates the main findings obtained in this study for in-vehicle central control interfaces, which automotive designers and manufacturers can adopt as a design reference. Applying tactile feedback solutions for in-vehicle central control interfaces that match the user's emotional experience improves the user's driving experience and creates positive value for the automotive brand.

The present study has some limitations. Firstly, the results in this study obtained subjective emotion states from drivers for the short term, whereas emotions are dynamic, and the driving task is continuous. Further research should focus on the long-term effects of tactile feedback on emotional states. Secondly, when driving real vehicles, users experience vibrations from the road surface and the vehicle itself. The absence of real-world environmental influences might imply that participants did not receive the complete tactile feedback experience, which affects task execution and user perception (Tang et al., 2023). In addition, the experiment did not require participants to perform specific driving tasks. Although participants were asked to remain attentive to road conditions, participants were less likely to perceive the risks associated with driving, which may have led to changes in their subjective rating. To address these two issues, more dynamic driving

	Overall	Simple NDRT	Complex NDRT
Touchscreens virbration feedback	+ −	●	●
Physical button force feedback	− +	●	●
Low intensity	− −	●	●
Medium intensity	+ +	●	●
High intensity	+ +	●	●
Touchscreens virbration feedback-Low intensity	− −	−	−
Touchscreens virbration feedback-Medium intensity	+	+	+
Touchscreens virbration feedback-High intensity	+ +	+	+
Physical button force feedback-Low intensity	●	−	●
Physical button force feedback-Medium intensity	●	+	●
Physical button force feedback-High intensity	●	−	●

Valence − + Dominance − +
Arousal − + NS ●

Fig. 11. The overview of main findings in this study.

scenarios in which a simulator or real-world assessments are combined can be considered to investigate the potential impact of in-vehicle central control interface tactile feedback. Thirdly, although the within-subjects design used in the study attenuated the effects of individual differences on tactile sensitivity and the previous experience with touchscreens or physical buttons on the results, it also meant that the NDRTs were repeatedly exposed, which may have created a learning effect on the participants. Further research could be optimized in terms of experimental design, and more studies designed with a broader range of participants could be conducted as the participants in this study were mainly young and middle-aged drivers whose tactile perception, driving experience and cognitive workload tolerance are not necessarily representative of a broader range of drivers. A more in-depth understanding of the differences between age groups or driving experience could enrich the tactile feedback design knowledge database and improve the tactile feedback design of automotive HMI designers and manufacturers.

5. Conclusion

This study aimed to investigate the effect of tactile feedback mode and intensity on the emotional state of drivers within the context of driving scenarios. Our findings suggest that, compared to physical button tactile feedback, moderate touchscreen tactile feedback induces a more positive emotional state in drivers. Specifically, the intensity of touchscreen tactile feedback is positively correlated with the emotional valence level of drivers. When drivers interact with physical buttons that provide higher-intensity tactile feedback, their emotional valence decreases. Notably, while operating complex NDRTs, physical button tactile feedback leads to decreased emotional valence levels, with the differences resulting from feedback intensity not being significantly pronounced. As a result, it is recommended to avoid requiring users to employ physical buttons for excessively complex NDRTs to maintain their positive emotional state. Furthermore, the research findings also indicate that task efficiency and accuracy in NDRTs can serve as robust indicators for predicting the emotional state of drivers. It is necessary to intervene in and take preventive measures in the design of tactile feedback to ensure an emotional experience in in-vehicle control interfaces for drivers, thereby enhancing product market competitiveness.

Ethical approval

This research has received the ethical approval from Ethical Review Committee (NBU-2023-571), Ningbo University. We confirm that all research is conducted in accordance with the relevant guidelines/provisions of the 1964 Declaration of Helsinki where human participants are involved.

CRediT authorship contribution statement

Faren Huo: Writing – review & editing, Supervision, Methodology, Conceptualization. **Tai Wang:** Writing – original draft, Methodology, Data curation, Conceptualization. **Fei Fang:** Writing – review & editing, Visualization, Data curation. **Cong Sun:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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