When Do Users Prefer Voice-Controlled Systems in Vehicles? A Survey of Chinese Drivers

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ABSTRACT

Voice control systems (VCS) are becoming increasingly common in modern vehicles, but concerns are still expressed by drivers about adopting them in smart cockpits. Previous research on privacy and recognition accuracy may not fully address users' needs regarding VCS. Additionally, studies on the safety impacts of different interaction modalities may also not reveal drivers' preference for interaction modalities, given that drivers' choice may not be solely based on interaction safety. Thus, to better understand and optimize VCS design, an online survey in China was conducted to investigate drivers' choices between VCS and manual interactions. In total, we analyzed 168 drivers' preferred interaction modality (i.e., either VCS or manual interactions) in different scenarios defined by passenger presence (i.e., present versus absent), traffic complexity (i.e., low versus high traffic density), roadway type (i.e., urban road versus highway), and task characteristics (i.e., six in-vehicle interaction tasks). It was found that compared to manual interactions, drivers prefer VCS when driving alone, driving on highways, and driving in complex traffic. Further, drivers prefer VCS when in-vehicle tasks are more distracting and time-demanding (e.g., compiling a text message). The preference for interaction modalities can also be affected by the characteristics of drivers: those with lower driving frequencies and higher VCS familiarity and those who perceived higher VCS usability tend to choose VCS as an interaction modality for in-vehicle interaction tasks. These findings offer insights for adaptive interface design and future optimization of VCS systems.

Keywords: Voice control system; interaction modalities; driving scenarios; roadway type; in-vehicle information systems (IVIS)

INTRODUCTION

In the past several decades, in-vehicle information systems (IVIS) have become increasingly prevalent in the smart cockpit of modern vehicles (*1*). The IVIS can allow drivers to get access to various types of in-vehicle functions, including controlling entertainment systems (e.g., selecting songs), making communication (e.g., making phone calls), changing in-vehicle settings (e.g., setting the temperature in the vehicle) and planning a trip (e.g., setting navigation) (*2*).

Traditionally, the IVIS interactions mainly relied on manual interactions (or MIs), which include physically haptic buttons and touch-based interactions. The physically haptic buttons have a long history in the automotive industry, and the physically haptic buttons allow drivers to interact with their vehicles by pressing the buttons embedded in the cockpit, through which drivers could obtain tactile feedback (*3*). However, due to its physical essence and limited cockpit space, physically haptic buttons could only support very limited functions and can hardly be updated once a vehicle is sold, which is less favored by users compared to touch-based interactions in recent years (*4–8*). In contrast, touch-based interactions could provide a graphical representation of buttons that allow drivers to interact with their vehicles through manual interactions with touch screens, such as tapping and swiping. The touch-based interactions have become increasingly common in recent years and even become the major interaction method in some vehicle models (e.g., Tesla Model 3). Though touch-based interactions offer great flexibility in in-vehicle functions, previous research has raised safety concerns on the implication of touch-based interactions in vehicles, as touch-based interactions can be visually distracting (*9*) in vehicles. For example, compared to no in-vehicle interaction tasks (the baseline), previous studies revealed that operating touch-based IVIS while driving can negatively influence driving performance, leading to reduced headways (*10*), larger maximum deceleration (*11*), more lane departures (*12*, *13*), slowed reaction to emergencies (*14*), reduced minimum time-to-collision (*7*), and increased variations in both longitudinal and lateral vehicle control (*7*). Interacting with touch-based IVIS can also impair visual scanning behaviors, leading to more frequent off-road glances (*13*, *15*). Further, touch-based IVIS can also be cognitively demanding (*16*). For example, it was found that when driving with touch-based IVIS tasks, drivers had more short blinks compared to that when driving was the sole task (*17*), indicating high cognitive load when interacting with touch-based IVIS (*18*).

To overcome the limitations of physical buttons and touch-based interactions, in recent years, more and more vehicles have been equipped with vehicle control systems (VCS). Given that the VCS allows drivers to interact with IVISs through spoken commands only with their hands on the wheel and eyes on the road (*19–21*) and that driving tasks are mainly visual and manual tasks, the VCS is believed to be less visual and manual distracting compared to physical buttons and touch-based interactions, according to the Multiple Resource Theory by Wickens (*22*). Indeed, some research has pointed out that the VCS impairs less on driving performance compared to touch-based interactions. For example, Zhang et al. (*23*) compared the effects of different interaction modalities (i.e., touch-based interactions, VCS, and gesture-based) on driving and visual performance. They found that VCS influenced less driving and visual performance and thus can be potentially safer compared to touch-based interactions.

However, though the advances in machine learning and natural language processing have made VCS increasingly accurate and reliable, the safety benefits of the VCS are still controversial. For example, two on-road studies found that using VCS can be both visually demanding (i.e., without providing appropriate feedback) (*24*) and cognitively demanding (as compared to natural conversations in vehicles) (*25*) if the VCSs are designed inappropriately. A more recent study found that the benefit of the VSCs did not always outperform touch-based interactions when considering their impairment on driving performance (*26*). In another study, Yager (*27*) found that when using voice-to-text applications (i.e., Siri or Vlingo), drivers' reaction times to a green light on the dashboard doubled and they exhibited fewer glances to forward roadways compared to that of the baseline when no non-driving-related tasks (NDRTs) were provided. In the study, it was also alerted to find that drivers felt safer when using VCS compared to manual text entry, which may potentially lead to increased engagement with VCS-based NDRTs in vehicles. This raises a concern about whether drivers can modulate their engagement with in-vehicle tasks offered in smart cockpits.

Though a large body of literature has focused on the optimization of VCS (e.g., Hua and Ng (*28*), Chang et al. (*29*)) and the impact of interaction modalities on driving performance (e.g., Ma et al. (*26*)), only a few studies have focused on drivers' willingness to adopt VCS and their perception of VCS. For example, Aldridge and Lansdown (1999) found that drivers' choice of speech-based interaction was influenced by their familiarity with the VCS features, frequency of use, and acceptability of manual controls. Chakraborty (*31*) found that drivers' attitudes (i.e., the perceived usefulness and the perceived ease-of-use) towards the VCS technology is a main predictor of their adoption of in-vehicle VCS. Another study by Sokol et al. (*32*) further found that users' acceptance of the system was positively associated with the robustness of the VCS to the background noise. However, the previous literature ignored the scenarios where the interaction can happen. Previous research on driver distraction found that drivers (especially experienced drivers) were able to self-regulate their NDRT engagement behaviors based on the complexity of the driving conditions (*33*, *34*) when the distraction task was voluntary (i.e., the drivers had the freedom to choose when and whether to engage in a task) (*35*). Given the gap between the objective and subjectively perceived distraction effects of the VCS (as pointed out in (*27*)), it is questionable whether drivers can select appropriate interaction modalities in vehicles under different scenarios.

Therefore, as a preliminary effort, this study aims to understand drivers' choices in using VCS for six common IVIS tasks under different scenarios. Being different from previous studies, in which the modalities of the interactions are involuntary (i.e., drivers had no choice in the modality of the in-vehicle tasks), this study focused on drivers' voluntary selection of interaction modalities under different scenarios. As this study mainly focuses on VCS, which mainly claims verbal resources, the physically haptic buttons, and touch-based interactions were aggregated as the modality of manual interaction in the study, as they both claim manual resources (*36*). In the study, the characteristics (i.e., visual distracting level, cognitive distracting level, manual distracting level, and the time demand for completing the tasks) of the in-vehicle tasks were quantified based on drivers' subjective perception of the tasks, as there can be a gap between objectively and subjectively task characteristics, and it is widely acknowledged that one's decision making is a subjective process (*37*). Given that previous research identified that environment-related factors (e.g., light levels, road conditions) can affect the adoption of IVIS (*4*), and that the traffic complexity (*38*) and roadway type (*39*) were found to be associated with self-regulation of distraction engagement, these factors were used to define the scenarios in our study. Further, as the passenger presence may raise privacy concerns when using VCS in vehicles (*40*) and user characteristics (e.g., age, experience with IVIS) may affect the adoption of IVIS (*4*), the demographic information of the users was also considered as a moderating factor of VCS adoption in our study. To this end, this study mainly focused on the following research questions (RQ):

RQ-1: Given the social dynamics and potential distractions of passengers, how does their presence influence a driver's preference between manual and voice controls when interacting with IVIS?

RQ-2: Different road conditions come with varying levels of cognitive demand. Thus, how do traffic complexity and roadway type inform a driver's choice between manual and voice-operated controls?

RQ-3: IVIS tasks differ in the amount of cognitive, visual, and temporal attention they require. How do these task demands shape a driver's predilection for manual versus voice controls?

RQ-4: Familiarity with technology, usability of technology, and overall driving experience can affect a driver's comfort level and efficiency with IVIS. How do these factors play into a driver's choice between manual and voice controls?

Overall, the contribution of this study is two-fold. Firstly, from the theoretical perspective, we explored and identified important factors that influenced drivers' use of VCS, which provided valuable insights for further empirical research. In terms of application, findings from this study would provide a better understanding of how drivers perceive different IVIS tasks in vehicles and when drivers prefer to use the VCS in vehicles, which could guide the design and improvement of VCS in the future.

METHODS

In this study, a survey-based approach was adopted. First, a questionnaire was designed and distributed online to collect the data related to drivers' demographic information (i.e., demographic variables), driving-related information (i.e., driving-related variables), interaction-related information (i.e., interaction-related variables), perceived distraction levels of six in-vehicle tasks (i.e., task-related variables) and their choice of interaction modalities under different scenarios. Then, a logistic regression model was constructed to investigate the factors influencing drivers' choice of interaction modalities, with drivers' preference being used as the dependent variable while demographic variables, driving and interaction-related variables, and task-related variables as the independent variables.

Questionnaire design

A questionnaire was designed to collect the data for this study, which contains four parts: (1) demographic information; (2) driving and in-vehicle interaction-related information; (3) perceived comparative distraction levels of selected tasks; and (4) Choice of interaction modalities under different scenarios. More details are presented in the subsequent sections.

Demographic information

As shown in **Table 1**, participants' demographic information was collected, including age, gender, education level, experience of general technology, and attitude towards new technologies. By adapting the survey questions from previous studies (*41*, *42*), we assessed drivers' self-reported experience of technologies in general and attitude towards new technologies using two questions, i.e., "*What is your level of experience with technologies (e.g., phone, computer, and camera)?*" with possible responses ranging from 1 ("*very inexperienced*") to 10 ("*very experienced*") and "To *which degree you consider yourself as an early adopter of technology?*" with possible responses ranging from 1 ("*absolutely no*") to 10 ("*absolutely yes*"). **Table 2** presents the distribution of all extracted demographic variables.

TABLE 1 Questions and extracted variables for demographic information, driving information, and in-vehicle interaction-related information

[Question Type] Questions	Descriptions of questions	Sources of Questions	Extracted Variables
[FI] What is your age in years of old?	Participants' self-reported age (in years of old).	Self-developed	Age
[SC] What is your gender?	Participants' self-reported gender.	Self-developed	Gender
[SC] What is your education level?	Participants' self-reported education level.	(*43*)	Education level
[LS] What is your level of experience with technologies (e.g., phone, computer, and camera)?	Participants' self-reported experience of technologies.	(*41*)	Technology experience
[LS] To which degree do you consider yourself an early adopter of technology?	Participants' self-reported attitude towards technologies.	(*41*)	Technology attitude
[FI] How long have you got your first driver's license (in years)?	Participants' self-reported year of licensure (in years).	Self-developed	Year of licensure
[SC] What is your driving frequency in the past year?	Participants' self-reported driving frequency.	Self-developed	Driving frequency
[SC] What is your frequency of using manual interactions (e.g., physically haptic buttons and touch-based interactions) during driving in the past year?	Participants' self-reported frequency of using manual interactions.	Self-developed	MIs frequency
[LS] Considering your experience, what is your level of familiarity with using manual interactions (e.g., physically haptic buttons and touch-based interactions) in the vehicle?	Participants' self-reported familiarity with manual interactions.	(*42*)	MIs familiarity
[LS] Considering your experience, what is your level of comfort when you are using manual	Participants' self-reported comfort level of using manual interactions.	(*42*)	MIs comfort level

[Question Type] Questions	Descriptions of questions	Sources of Questions	Extracted Variables
interactions (e.g., physically haptic buttons and touch-based interactions) in the vehicle?			
[LS] Ten items adapted from the System Usability Scale (SUS) (*44*) (e.g., I think that I would like to use manual interactions to perform in-vehicle interaction tasks frequently).	The usability of manual interactions evaluated by participants.	(*44*)	MIs usability
[LS] Five items adapted from Jian et al. (*45*) (e.g., the manual interactions are dependable.)	The trust in manual interactions reported by participants.	(*45*)	MIs trust
[SC] What is your frequency of using voice-controlled systems during driving in the past year?	Participants' self-reported frequency of using VCS.	Self-developed	VCS frequency
[LS] Considering your experience, what is your level of familiarity with using voice-controlled systems (e.g., communicating with the system with spoken command) in the vehicle?	Participants' self-reported familiarity with VCS.	(*42*)	VCS familiarity
[LS] Considering your experience, what is your level of comfort with using voice-controlled systems (e.g., communicate with the system with spoken command) in the vehicle?	Participants' self-reported comfort level of using VCS.	(*42*)	VCS comfort level
[LS] Ten items adapted from SUS (*44*) (e.g., I think that I would like to use voice-controlled systems to perform in-vehicle interaction tasks frequently).	The usability of VCS evaluated by participants.	(*44*)	VCS usability
[LS] Five items adapted from Jian et al. (*45*) (e.g., the voice-controlled system is dependable.)	The trust in VCS reported by participants.	(*45*)	VCS trust

Note: FI stands for fill-in-text. SC stands for single choice. LS stands for Likert scale.

TABLE 2 The distributions of the extracted demographic variables

Extracted Variable	Distributions	Extracted Variable	Distributions
Age[C]	M = 29.5 (SD = 5.1) Min = 19, Max = 46	MIs familiarity[C]	M = 8.2 (SD = 1.6) Min = 1, Max = 10
Gender[N]	- Male (n = 107) - Female (n = 61)	MIs comfort level[C]	M = 7.8 (SD = 1.6) Min = 3, Max = 10
Education level[N]	- Professional college or less (n = 36) - Bachelor (n = 110) - Master or above (n = 22)	MIs usability[C]	M = 63.8 (SD = 13.4) Min = 25, Max = 100
Technology experience[C]	M = 8.7 (SD = 1.2) Min = 5, Max = 10	MIs trust[C]	M = 3.9 (SD = 0.7) Min = 1, Max = 5
Technology attitude[C]	M = 8.9 (SD = 1.3) Min = 3, Max = 10	VCS frequency[N]	- Several times per year (n = 26) - Several times per month (n = 47) - Several times per week (n = 65) - Almost every day (n = 30)
Year of licensure[C]	M = 7.4 (SD = 4.0) Min = 1, Max = 22	VCS familiarity[C]	M = 7.8 (SD = 1.9) Min = 1, Max = 10
Driving frequency[N]	- Several times per year (n = 13) - Several times per month (n = 38) - Several times per week (n = 54) - Almost every day (n = 63)	VCS comfort level[C]	M = 7.6 (SD = 1.8) Min = 2, Max = 10
MIs frequency[N]	- Several times per year (n = 11) - Several times per month (n = 34) - Several times per week (n = 53) - Almost every day (n = 70)	VCS usability[C]	M = 60.1 (SD = 14.5) Min = 20, Max = 100
VCS trust[C]	M = 3.7 (SD = 0.7) Min = 1.8, Max = 5		

Note: C stands for continuous variables. N stands for nominal variables. M stands for Mean and SD stands for Standard Deviation.

Driving and in-vehicle interaction-related information

As shown in **Table 1**, the driving and in-vehicle interaction-related questions collected information regarding drivers' year of licensure, driving frequency in the past year, familiarity with manual interactions/VCS, frequency of using manual interactions/VCS, the comfort level of using manual interactions/VCS, their perceived usability of manual interactions/VCS, and their trust in manual interactions/VCS in the vehicle they drove most frequently in the past one year. The above-mentioned information was collected as they were found to be related to users' adoption of new technologies. For example, the familiarity with and comfort level of using advanced driver assistance systems were found to be positively associated with drivers' knowledge and acceptance of advanced driver assistance systems (*46*, *47*). The response to the familiarity of manual interactions/VCS ranged from 1 ("*very unfamiliar*") to 10 ("*very familiar*") (*41*); the response to the comfort levels of using manual interactions/VCS ranged from 1 ("*very uncomfortable*") to 10 ("*very comfortable*") (*41*). The perceived usability of manual interactions/VCS was assessed using the System Usability Scale (SUS) (*44*) with possible responses ranging from 1 ("*strongly disagree*") to 5 ("*strongly agree*"). For the ten items included in SUS, following (*44*), we summed the score distributions from each item and multiplied the sum of the scores by 2.5 to obtain the overall value of system usability. It should be noted that, in SUS, for items 1, 3, 5, 7, and 9, the score is the user's rating minus 1; while items 2, 4, 6, 8, and 10 are reversed and the score is 5 minus user's rating (*44*). Further, following previous studies (*41, 48*), a five-item scale developed by Jian et al. (*45*) was adopted to evaluate users' trust in manual interactions/VCS, and the responses ranged from 1 ("*strongly disagree*") to 5 ("*strongly agree*"). We averaged the values of five items to obtain the trust score (*45*).

Perceived distraction levels of selected IVIS tasks

In this study, six common IVIS tasks that drivers usually perform were selected based on a review of previous literature (e.g., Bach et al. (*49*), Bilius & Vatavu (*50*), Ma et al. (*26*), Simmons et al. (*19*)), including (1) adjusting the temperature in the vehicle to a specific temperature (T1); (2) selecting a specific song in the favorite music list to play (T2); (3) making a phone call to a specific person in the contact list (T3); (4) compiling and sending a text message (T4); (5) navigating to a specific destination (T5); and (6) Opening or closing the window (T6). Inspired by Regan et al. (*51*) and Young et al. (*52*), we evaluated drivers' perceived distraction levels of selected tasks using manual interactions based on four dimensions, i.e., visual distraction level ("how much off-road visual attention is needed by the task"), manual distraction level ("how much off-wheel manual interaction is needed by the task"), cognitive distraction level ("how much cognitive attention is needed by the IVIS task"), and time demand ("how much time is needed to complete the task"). For each of the four dimensions, drivers were required to rank the six IVIS tasks in descending order, and the distraction level was assigned from L6 ("high") to L1 ("low") from the highest to the lowest. In other words, each IVIS task had five attributes, i.e., task type and distraction level in four dimensions.

Choice of interaction modalities under different scenarios

The scenarios were defined by four dimensions: (1) task types (T1 to T6); (2) passenger presence (i.e., passenger present versus passenger absent); (3) roadway type (i.e., urban road versus highway); and (4) traffic complexity (i.e., low versus high traffic complexity). It should be noted that the passenger here was defined as a passenger that the driver was not familiar with (e.g., a colleague) given that privacy can be a greater concern when taking a ride with unfamiliar people (*40*). The traffic complexity was defined as the traffic density, in which high traffic complexity referred to high traffic density, while low traffic complexity referred to low traffic density (*53*). We did not set specific thresholds for traffic density but asked the respondents to imagine the scenarios that they believed were with high/low density, as different drivers may have different perceptions of vehicle control difficulty even with the same level of absolute traffic density. A within-subject design was adopted in this study, leading to 48 scenarios (i.e., 6 task types by 2 passenger presence levels by 2 roadway type levels by 2 traffic complexity levels) for each participant. All participants indicated their preferred interaction modality (VCS or manual interactions) in these 48 scenarios based on their past experiences, which aimed to obtain participants' responses in a conceptually understood situation (see **Table 3**). The order of the 48 scenarios was completely randomized for each participant.

To avoid misunderstanding the interaction modalities, we defined the VCS and manual interactions at the beginning of this part of the questionnaire. Specifically, the VCS was defined as "*As a driver, using VCS means that you are communicating with the in-vehicle voice system through dialogues to perform the interaction task*"; and the manual interaction was defined as "*As a driver, using* manual interactions *means that you are performing the interaction task by using part of your body (e.g., fingers) to use physical buttons or touch screens*".

TABLE 3 Questions used to obtain participants' preferences of interaction modalities

<table>
<tr><th>Scenario Factors</th><th>Questions for
Different Scenarios</th><th>Response</th></tr>
<tr><td>Task type:
(1) adjust the temperature in the vehicle to a specific temperature
(2) select a specific song in the favorite music list to play
(3) make a phone call to a specific person in the contact list
(4) compile and send a text message
(5) navigate to a specific destination
(6) open or close the window</td><td rowspan="4">Please answer the question based on your experience:

When you are [Passenger presence] on the [Roadway type], the [Traffic complexity], at this time if you want to [Task type], which kind of interaction method will you use?

For example:
When you are driving alone on an urban road, the traffic density is high, at this time if you want to compile and send a text message, which kind of interaction method will you use?</td><td rowspan="4">- VCS
- Manual interactions</td></tr>
<tr><td>Passenger presence:
(1) driving alone
(2) driving with a colleague</td></tr>
<tr><td>Roadway type:
(1) urban road
(2) highway</td></tr>
<tr><td>Traffic complexity:
(1) traffic density is low
(2) traffic density is high</td></tr>
</table>

Participants

Participants of this study were recruited through online posters in vehicle forums and advertisements in interest groups of car owners on social media (e.g., WeChat group of car owners) in China. Those who indicated that their vehicle had no VCSs that could perform the tasks in the study were not allowed to fill out the questionnaire (using a logic question at the beginning of the survey). As a result, in total, 524 participants filled out the questionnaire; incomplete responses were not allowed to be submitted in the questionnaire system and thus were not recorded. As shown in **Figure 1**, to ensure the validity of self-reported data from online participants and obtain high-quality data, we applied the attention check, logic check, and survey completion time check following previous studies (*54*, *55*). The attention check and logic check questions were presented in the same sequence for all participants. Specifically, in the attention check, a simple question (e.g., "*If you are paying attention to answer this questionnaire, please select VCS as the answer for the current question*") was used and 118 participants who failed the attention check were excluded. For the logic check, we asked drivers to indicate their agreement to the statement "*I never used a mobile phone or computer/tablet before*" with possible responses ranging from 1 ("*Strongly Disagree*") to 5 ("*Strongly Agree*"). Given the online questionnaire can only be answered using electronic devices (e.g., smartphone, computer, or tablet), it was assumed that all drivers who focused on the questionnaire should answer "*Strongly Disagree*" or "*Disagree*" to this question and 176 participants were excluded in this step. For the survey completion time check, the average estimated time for carefully completing the 102 questions was 10 minutes, and the lower threshold of completion time was set to 5 minutes (50% of the average completion time) (*43*, *56*) and 62 participants were excluded. As a result, 168 valid responses were kept for analysis in this study. Respondents who provided valid survey samples were compensated with 5 RMB. This study was approved by the Human and Artefacts Research Ethics Committee at the Hong Kong University of Science and Technology (HREP-2023-0130), and all participants provided online informed consent for this study through electronic signatures.

Figure 1 The screening process of the survey responses

Variable extraction

Table 1 summarizes questions and extracted variables, and **Table 2** presents the distribution of the variables for demographic information, driving information, and in-vehicle interaction-related information. In this study, drivers' self-reported usability of manual interactions and VCS were calculated following previous research (*44*), and the possible ranges for the usability of manual interactions and VCS were from 0 to 100, with larger values indicating better usability. Further, drivers' self-reported trust in manual interactions and VCS were calculated by averaging the responses of all five questions (*45*, *48*) and the possible ranges were from 0 to 5, with larger values indicating higher trust. All rest demographic information, driving information, and in-vehicle interaction-related information are self-explanatory and can be used directly.

Statistical analysis

A logistic regression model was constructed using PROC GENMOD in SAS OnDemand for Academics. The dependent variable was the drivers' preferred interaction modality (i.e., manual interactions versus VCS) in different scenarios. For each participant, we collected their responses in 48 different scenarios, leading to 8064 (168 participants and 48 scenarios per participant) data points in the collected dataset. The repeated measure was accounted for by the generalized estimating equations (GEE) method.

The independent variables in the full model included demographic factors (i.e., age, gender, education, technology experience and technology attitude), driving-related factors (i.e., year of licensure and driving frequency), interaction-related factors (i.e., MIs familiarity, MIs frequency, MIs comfort level, MIs trust, MIs usability, VCS familiarity, VCS frequency, VCS comfort level, VCS trust, VCS usability), task-related factors (i.e., task type, and every respondent's self-reported visual distraction level, manual distraction level, cognitive distraction level and time demand level of each task) and scenario-related factors (i.e., passenger presence, roadway type, and traffic complexity). All two-way interactions among task type, passenger presence, roadway type, and traffic complexity were also included in the model as they defined the scenarios and were the major variables of interest. For the model selection, we first fitted a full model with all independent variables. Then we applied a backward stepwise selection method (i.e., iteratively fitted new models by removing independent variables one by one) (*57*) based on the Quasi-likelihood under the Independence model Criterion (QIC) statistic (*58*). The final model was obtained when the QIC did not decrease.

RESULTS

Perceived distraction levels of selected tasks

Figure 2 presents the distraction levels of selected tasks on four distraction dimensions, in which insignificant pair-wise comparisons were marked in red. In general, we found that participants perceived

T4 ("compiling and sending a text message") as the most distracting task while T6 ("Opening or closing the window") was the least distracting task on all distraction dimensions. Specifically, on cognitive distraction dimension, T4 > T3 > T1 ≈ T2 ≈ T5 > T6; on manual distraction dimension, T4 > T1 ≈ T2 ≈ T3 ≈ T5 > T6; on time demand dimension, T4 > T1 ≈ T2 ≈ T3 ≈ T5 > T6; and on visual distraction dimension, T4 > T2 ≈ T3 ≈ T5 > T1 > T6.

Figure 2 Participants' perceived distraction levels of selected tasks. Boxplots represent the five-number summary, along with the mean depicted through blue triangles. The insignificant pairwise comparisons are highlighted in red pairs (*p* > .05).

Factors associated with drivers' choice of interaction modalities

Table 4 summarizes the Wald statistics for type 3 generalized estimating equations (GEE) analysis of the final model. It was found that driving frequency, VCS familiarity, VCS usability, passenger presence, task type, and time demand were significantly associated with drivers' choice of interaction modalities in different scenarios. Further, a significant interaction effect between roadway type and traffic complexity was also observed. All significant ($p < .05$) Tukey post-hoc comparisons (*59*) for significant predictors were reported.

TABLE 4 Wald statistics for type 3 GEE analysis of the final model

Independent Variable	χ^2-value	*p*
Gender	$\chi^2(1) = 3.34$	.07
Year of Licensure	$\chi^2(1) = 2.94$	.09
Driving Frequency	$\chi^2(3) = 11.73$	.008*
MIs Familiarity	$\chi^2(1) = 2.38$	.12
MIs Frequency	$\chi^2(3) = 7.15$	.07
VCS Familiarity	$\chi^2(1) = 5.70$	.02*
VCS Frequency	$\chi^2(3) = 6.13$	.11
Trust in MIs	$\chi^2(1) = 3.12$	.08
Trust in VCS	$\chi^2(1) = 2.02$	.16
VCS Usability	$\chi^2(1) = 5.91$	.02*
Passenger Presence	$\chi^2(1) = 17.69$	< .0001*
Roadway Type	$\chi^2(1) = 31.90$	< .0001*
Traffic Complexity	$\chi^2(1) = 64.20$	< .0001*
Roadway Type*Traffic Complexity	$\chi^2(1) = 23.07$	< .0001*
Task Type	$\chi^2(5) = 39.26$	< .0001*
Time Demand	$\chi^2(5) = 12.49$	.03*

* marks significant variables ($p < .05$).

RQ-1: Influence of passenger presence

It was found that, compared to driving with a passenger present, drivers were more likely to use VCS to perform the selected tasks when they were driving alone (i.e., passenger absent), with an odds ratio (OR) of 1.41 and a 95% confidence interval (95%CI) between 1.20 and 1.66, $\chi^2(1) = 17.69$, $p < .0001$.

RQ-2: Influence of roadway type and traffic complexity

For the significant interaction effect between roadway type and traffic complexity, it was found that, when the traffic complexity was low, drivers were less likely to use VCS on urban roads compared to that on highways (OR = 0.60, 95%CI: [0.51, 0.70], $\chi^2(1) = 39.41$, $p < .0001$). When the traffic complexity was high, no significant difference in drivers' preferred interaction modality was observed ($p > .05$). On the other hand, compared to the situation with lower traffic complexity, we found that drivers tended to use VCS when the traffic complexity was high, but to different extents on different types of roadways (‘*Urban Roads*’: OR= 3.32, 95%CI: [2.56, 4.30], $\chi^2(1) = 82.55$, $p < .0001$; ‘*Highways*’: OR= 2.20, 95%CI: [1.71, 2.84], $\chi^2(1) = 36.56$, $p < .0001$).

RQ-3: Influence of task type and time demand

Table 5 and **Table 6** summarize the odds ratios of choosing VCS in post-hoc comparisons of task type and time demand. For example, the left top cell in Table 5 indicates that compared to selecting a specific song in the favorite music list to play, drivers were less likely to use VCS when adjusting the temperature in the vehicle to a specific temperature, with an OR of 0.79, 95% CI between 0.64 and 0.98, and $\chi^2(1) = 4.39$ ($p = .04$). Although not all pairwise comparisons were significant, we found that drivers were more likely to use VCS when they needed to perform tasks with higher time demand (i.e., significant ORs that are over one mainly located in the lower left corner of **Table 6**).

TABLE 5 Pair-wise comparisons for odds ratios [95%CI] of using VCS between different tasks

		T1	T2	T3	T4	T5
Tasks being compared to	T2	**0.79 [0.64, 0.98] $\chi^2(1) = 4.39$, $p = .04$**	-	-	-	-
	T3	0.89 [0.69, 1.16] $\chi^2(1) = 0.68$, $p = .4$	1.13 [0.87, 1.47] $\chi^2(1) = 0.83$, $p = .4$	-	-	-
	T4	**0.76 [0.60, 0.98] $\chi^2(1) = 4.49$, $p = .04$**	1.02 [0.82, 1.27] $\chi^2(1) = 0.03$, $p = .9$	1.13 [0.87, 1.48] $\chi^2(1) = 0.88$, $p = .4$	-	-
	T5	**0.78 [0.62, 0.97] $\chi^2(1) = 4.71$, $p = .03$**	0.98 [0.79, 1.22] $\chi^2(1) = 0.04$, $p = .9$	0.87 [0.67, 1.13] $\chi^2(1) = 1.12$, $p = .3$	**1.28 [1.03, 1.60] $\chi^2(1) = 4.75$, $p = .03$**	-
	T6	**2.16 [1.55, 3.02] $\chi^2(1) = 20.45$, $p < .0001$**	**2.72 [1.91, 3.87] $\chi^2(1) = 31.06$, $p < .0001$**	**2.41 [1.71, 3.39] $\chi^2(1) = 25.39$, $p < .0001$**	**2.12 [1.55, 2.90] $\chi^2(1) = 22.41$, $p < .0001$**	**2.77 [1.98, 3.88] $\chi^2(1) = 35.35$, $p < .0001$**

Note: T1: adjusting the temperature in the vehicle to a specific temperature; T2: selecting a specific song in the favorite music list to play; T3: making a phone call to a specific person in the contact list; T4: compiling and sending a text message; T5: navigating to a specific destination; T6: Opening or closing the vehicle window. Significant comparisons are highlighted in bold.

TABLE 6 Odds ratios [95%CI] of using VCS for pair-wise comparisons between different time demand levels of tasks

		L6	L5	L4	L3	L2
Time demand levels being compared to	L5	1.06 [0.83, 1.35] $\chi^2(1) = 0.23$, $p = .6$	-	-	-	-
	L4	1.08 [0.86, 1.37] $\chi^2(1) = 0.47$, $p = .5$	1.02 [0.78, 1.34] $\chi^2(1) = 0.02$, $p = .9$	-	-	-
	L3	1.31 [0.99, 1.71] $\chi^2(1) = 3.84$, $p = .06$	1.23 [0.98, 1.56] $\chi^2(1) = 2.99$, $p = .08$	1.21 [0.93, 1.57] $\chi^2(1) = 1.96$, $p = .16$	-	-
	L2	**1.32 [1.04, 1.66] $\chi^2(1) = 5.10$, $p = .02$**	1.24 [0.98, 1.57] $\chi^2(1) = 3.10$, $p = .08$	1.21 [0.94, 1.55] $\chi^2(1) = 2.22$, $p = .14$	1.01 [0.81, 1.24] $\chi^2(1) = 0.01$, $p = .98$	-
	L1	**1.64 [1.18, 2.27] $\chi^2(1) = 8.70$, $p = .003$**	**1.54 [1.13, 2.10] $\chi^2(1) = 7.60$, $p = .006$**	**1.51 [1.08, 2.11] $\chi^2(1) = 5.85$, $p = .02$**	1.25 [0.92, 1.70] $\chi^2(1) = 2.04$, $p = .15$	1.25 [0.92, 1.69] $\chi^2(1) = 2.03$, $p = .15$

Note: L1, L2, L3, L4, L5, and L6 were time demand levels in ascending order. Significant comparisons are highlighted in bold.

RQ-4: Influence of driving frequency, VCS familiarity, and VCS usability

Firstly, drivers’ driving frequency was negatively associated with their preference to use VCS. Specifically, the drivers who almost did not drive (i.e., with a driving frequency of ‘*Several times per* *year*') reported a higher likelihood of using VCS to perform the IVIS task compared to those who drove '*several times per week*' (OR = 2.38, 95%CI: [1.13, 4.99], $\chi^2(1) = 5.25$, $p = .02$). Further, drivers who drove '*almost every day*' were less likely to use VCS compared to drivers who almost did not drive (OR = 0.32, 95%CI: [0.16, 0.65], $\chi^2(1) = 10.04$, $p = .002$) and compared to those who drove '*several times per month*' (OR = 0.54, 95%CI: [0.30, 0.96], $\chi^2(1) = 4.29$, $p = .04$). At the same time, it was found that every 1-unit increase in VCS familiarity and VCS usability led to a 1.15 (95%CI: [1.03, 1.29], $\chi^2(1) = 5.70$, $p = .02$) and 1.02 (95%CI: [1.01, 1.03], $\chi^2(1) = 5.91$, $p = .02$) multiplicative increase in the odds of using VCS, respectively. No other significant pairwise comparisons have been observed.

DISCUSSIONS

Through the analyses based on 168 drivers' responses in an online survey, we investigated drivers' preferred modalities when interacting with IVISs in different scenarios as defined by task characteristics, passenger presence, roadway type, and traffic complexity. We further examined how drivers' preferences can be moderated by drivers' demographic characteristics, driving experience, and their experience with and attitudes towards general technology and manual interactions/VCS in vehicles.

RQ-1: Influence of passenger presence

We found that users' preference for interaction modalities varies under different conditions. Specifically, drivers were more likely to use VCS when they were driving alone, as compared to driving with passengers. It is possible that when driving with an unfamiliar passenger, drivers may feel more obligated to engage in conversation, and thus find it less convenient to use VCS. It is also possible that talking to a "robot" in front of a stranger would raise privacy concerns (*40*) and is also socially embarrassing (*60*).

RQ-2: Influence of roadway type and traffic complexity

The traffic complexity and roadway type in a scenario can also affect drivers' preference for VCS – both are associated with driving workload and drivers' perceived risk. In general, as expected, we found that with the increase in traffic complexity, drivers were more inclined to choose VCS compared to manual interactions, as the VCS conflicts less with the visual-manual demands in driving tasks (*6*) compared to manual interactions. This can be explained by the multiple resources theory by Wickens (*22*), compared to the major mental resource required by VCS (i.e., verbal), manual interactions required the same mental resources as the driving task (i.e., visual and manual) and thus were more likely to interfere with the driving task. Further, drivers' choice of interaction modality seemed to be more sensitive to the traffic complexity on urban roads (i.e., with higher traffic complexity, the OR of choosing VCS on urban roads was larger compared to that on highways), potentially because of the already-high preference for VCS on highways as a result of high driving task demands on highways. Specifically, driving at a relatively high speed on highways may have increased the perceived risk on highways (*61*), thus drivers may prefer to keep their hands on the wheel and eyes on the road. In other words, drivers' visual and manual resources are more occupied on highways (*22*), and they are more inclined to avoid visual-manual distractions on highways compared to on urban roads, as has been pointed out as self-regulation of distraction engagement in previous studies (*39*).

RQ-3: Influence of task type and time demand

This study reveals that drivers would consider the distracting level of a task and the time demand of a task when choosing the interaction modalities. It should be noted that, as the manual distraction level, visual distraction level, and cognitive distraction level were not included in the final model, we will discuss the influence of these dimensions on the choice of interaction modality based on the perceived level of these dimensions from all respondents, instead of from respondent's own perceived level, while the perceived time demand is based on respondent's judgment. In general, when a task is more distracting if performed through manual interactions, drivers would prefer VCS. For example, the task of opening and closing the window was perceived as the least distracting on cognitive, visual, and manual dimensions and it was least likely to be performed by VCS. This is potentially because the drivers are inclined to choose the modalities that are perceived as less distracting to avoid potential deterioration of driving performance (*62*). At the same time, when a task was perceived as more time-demanding if performed using manual interactions, drivers preferred VCS as the interaction modality for this task. This would have some practical value. Specifically, VCS may be more suitable for tasks that require a longer interaction time or that involve multiple steps or subtasks, as it allows drivers to interact with the system more naturally and conversationally. However, it should be noted that the four attributes we investigated in this study did not fully reveal drivers' VCS preferences. For example, although "compiling and sending a text message" was more distracting compared to "selecting a specific song in the favorite music list to play" and "making a phone call to a specific person in the contact list", drivers' preference to use VCS did not differ across these tasks. Other characteristics of the tasks may affect drivers' preferences, and this deserves further investigation.

RQ-4: Influence of driving frequency, VCS familiarity, and VCS usability

Besides the scenario and task characteristics, we found that drivers' preference for interaction modalities can be moderated by several other factors. It was found that drivers who drove less frequently preferred VCS when performing the IVIS tasks explored in the study. It is possible that drivers who drove less frequently were less experienced and thus they were more inclined to choose the modalities that they believed to be less distracting, as VCS allows drivers to keep their hands on the wheel and eyes on the road, reducing the need for manual and visual attention that is required when using manual interactions (*62*). This assumption echoes a positive relationship observed in our study, i.e., the more distracting a manual interaction task was, the more likely the drivers preferred VCS (e.g., drivers preferred manual interaction for opening and closing windows). At the same time, it is also possible that drivers with lower driving frequencies were less familiar with the in-vehicle controls and the layout of the touch-based interfaces and thus they might find VCS to be more intuitive and easier to use. Further, we found that drivers tended to use VCS when they were more familiar with VCS and had higher perceived usability of VCS. Firstly, those who are more familiar with VCS are more aware of the instructions that the VCS can understand and thus may make fewer errors when using VCS (*19*). This in turn can lead to faster and more efficient use of the VCS and make VCS more appealing to these users. Secondly, the drivers who reported higher perceived usability of VCS are the drivers who find the VCS to be more intuitive, easy to use, and less mentally demanding compared to touch-based interfaces (*63*). Thus, these drivers are more inclined to use VCS in more demanding situations. Finally, it is also possible that higher familiarity and perceived usability of VCS may be related to individual differences in technology adoption and preference. In other words, those who prefer VCS are those who are more comfortable with new technologies.

Limitations and future research

Several limitations of this study should be noted here. Firstly, the readers should be aware that the conclusions are based on survey studies. Although we have tried to control the validity of self-reported data, drivers' stated preference and their actual behaviors may still be different. Our results should be carefully interpreted by taking this into consideration and future research may overcome this through empirical methods, for example, by investigating drivers' preferred interaction modality under different scenarios using driving simulators, on-road experiments, or naturalistic studies, similar to what have been adopted in (*64–66*). However, it should be noted that the survey-based study can include a more diverse driver population compared to driving simulator studies and the findings in our study can supplement the findings from future driving simulation studies. Second, we only considered limited characteristics of the scenarios, which may not fully capture the complex driving scenarios that drivers may encounter. Thus, future observational studies are needed to further validate our findings. Besides, we only considered six IVIS tasks and four dimensions of the tasks in the study. As mentioned previously, we have already observed inconsistency between the ranking of the task dimensions and drivers' VCS preference. More attributes of the IVIS tasks (e.g., the location of the manual-interaction-based interface) and driver characteristics (e.g., driving styles) should be considered to better understand users' choice of interaction modalities in vehicles. Further, although our focus was to compare drivers' general preferences for VCS over manual interactions under different scenarios, it is still possible that the capabilities of different VCSs may vary, thus drivers may have different perceptions of VCSs with different capabilities, which may potentially influence their choices of modalities. Future studies could resolve these issues by providing the same IVIS system for participants in controlled experiments. Finally, it should be noted that the current study did not include the effect of driving automation as our main interest was drivers' preferences of interaction modalities when there were potential resource conflicts between driving tasks and in-vehicle information tasks, future research may further explore driver' preferences of interaction modalities when the driving automation was available.

CONCLUSIONS

In this study, based on the data collected from 168 drivers, we examined the effects of demographic factors (e.g., age, gender, education), driving-related factors (e.g., driving frequency, year of licensure), environmental factors (e.g., passenger presence, roadway type, and traffic complexity), and task characteristics (e.g., task type) on drivers' choice of interaction modalities (i.e., manual interactions and VCS). In contrast to previous studies that mainly focused on the effects of different interaction modalities on driving performance or traffic safety, our study provides valuable insights into drivers' preferred in-vehicle interaction modalities in different scenarios. Key findings and conclusions from this study are summarized as follows:

- Drivers' choice of the interaction modality is associated with the driving scenarios: drivers preferred VCS when they were driving alone, driving on highways, and driving in an environment with high traffic complexity.
- Drivers have different preferences of interaction modalities for different tasks: when tasks are more distracting and more time demanding, drivers prefer VCS over manual interactions.
- The preference for interaction modalities can be affected by the characteristics of drivers: those with lower driving frequencies and higher VCS familiarity and those who perceived higher VCS usability tended to choose VCS as an interaction modality for IVIS tasks.

The findings from this study provide insights for understanding drivers' choice of interaction modalities under different scenarios, which could guide the design of customized or adaptable in-vehicle interactions in smart cockpits from driving safety and user satisfaction perspectives of view.

AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: C.H., D.H.; data processing: C.H., S. Y.; analysis and interpretation of results: C.H., S.Y., W. X., D.H.; draft manuscript preparation: C.H., S.Y., W. X., D.H. All authors reviewed the results and approved the final version of the manuscript.

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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