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Okkeun Lee and Hyunmin Kang *

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Individual Differences in Signal Perception for the Take-over Request in Autonomous Driving

Okkeun Lee[1] and Hyunmin Kang[2,*]

[1] Department of Mechanical Engineering, Stanford University, Stanford, CA 94305, USA; okkeun@stanford.edu
[2] Stanford Center at the Incheon Global Campus, Stanford University, 119, Songdomunhwa-ro, Yeonsu-gu, Incheon, South Korea; neets@stanford.edu
* Correspondence: neets@stanford.edu

Abstract: In the context of partial autonomy, where autonomous vehicles and humans share control of the vehicle, bringing out-of-the-loop drivers back into the loop is a significant challenge. While warning signal design guidelines are commonly used to provide alerts, few studies have examined each signal in depth with an emphasis on the autonomous environment. This study aims to fill this gap by investigating visual, auditory, and tactile stimuli and modifying their sub-attributes to explore variations related to age, gender, and other individual backgrounds. A driving simulator was utilized to create a realistic driving environment and measure participants' reaction times in takeover request situations. Analysis of the data revealed correlations between age and reaction times for auditory and tactile signals, with interaction effects observed between age and sub-attribute intensity. Additionally, participants exhibited varying reaction time patterns in response to different sub-attribute intensities. By evaluating individual differences in perception based on modality characteristics, often overlooked in prior research, this study serves as a foundational contribution to future research in the field.

Keywords: take over request; signal perception; autonomous driving; individual difference; warning signal; modality

1. Introduction

In recent years, the interaction between autonomous driving and humans has been the subject of a great deal of research, with numerous studies conducted on the topic. The Society of Automotive Engineers (SAE) and the National Highway Traffic Safety Administration (NHTSA) have been continuously revising the interactions pertaining to the degree of automation in autonomous driving. In [1], they emphasized the significance of safety, performance, and user satisfaction as critical criteria for ergonomic design, and they suggested that the relative importance of various technologies may vary based on the stage of autonomous driving. Safety is always the most essential factor, especially in the early stages of autonomous driving, because vehicle accidents directly affect human lives. However, as the use of autonomous vehicles as a service becomes more prevalent and fully autonomous driving becomes more ubiquitous, design satisfaction may also become a crucial factor.

Takeover Request (TOR) is one of the most researched topics in autonomous driving, especially in stages 2 and 3 of the SAE standards, where the driver and the vehicle share driving responsibilities. Multiple subdomains of TOR research, including signaling time, modality, location, and error, are centered on system aspects, while mental models, situational awareness, and trust are centered on the human factor. On the basis of ergonomic research, the characteristics and effects of the three primary signaling modalities (visual, auditory, and tactile) have been extensively analyzed, and guidelines for selecting stimuli have been established.

In circumstances involving partial autonomy, the driver and vehicle must work together to complete the primary driving task. Different ages, levels of expertise, and personal histories result in distinct driving strategies and visual attention levels. In scenarios involving partially autonomous driving, it is crucial that the vehicle signal the human driver for a takeover request (TOR) and that the human driver recognize the signal promptly and accurately. To investigate whether an individual's background affects signal perception, we reviewed signaling guidelines in a traditional TOR scenario and conducted an experiment to determine how individuals respond to and prefer various modalities. Our research queries centered on determining the impact of gender, age, and other personal characteristics on responses to distinct signals. Specifically, one of our key research questions is whether people's reaction times and preferences change linearly or cascade as the detailed characteristics of each modality's signal (e.g., pitch for auditory or amplitude for tactile) change.

2. Related Works

We began by examining the characteristics of the stimuli used as TOR cues for each modality in previous studies. To do so, we reviewed how stimuli used in in-vehicle warning systems have been studied and examined the detailed characteristics of the stimuli. We then reviewed the literature on individual differences in signal perception and driving, and conducted an experiment to determine whether there are individual differences in signal perception in TOR.

2.1. Warning Signal Design in Autonomous Vehicle

Warning signals can be implemented in a variety of ways within the context of autonomous vehicles in order to convey vital information to the driver or user. During manual driving, warning signals typically signify problems with vehicle systems or interactions with other vehicles or the surrounding environment. A collision warning may be activated, for instance, when the vehicle approaches the vehicle in front of it, when it deviates from its lane, or when a rear-view camera is used for parking. At Level 3 and higher, when the vehicle is partially capable of performing the entire driving task, alerts can be provided continuously to keep the driver notified of the driving situation. These alerts also prompt the driver to regain control when the system loses control of the vehicle. In a scenario of fully autonomous driving, where the vehicle handles the entire driving task and the human assumes the character of a service user, notifications can be used to indicate critical situations or to provide content-related alerts during service interactions. In-vehicle alerts are typically categorized as visual alerts displayed on instrument panels or screens, auditory alerts delivered via in-vehicle speaker devices, and tactile alerts conveyed via vibration pads affixed to the steering wheel or seat. Individuals may receive these notifications via a single stimulus or via a combination of multiple modalities, known as multimodal alerts.

Each modality of autonomous vehicle warning signals has its own advantages and disadvantages. Visual alerts can convey information through words or icons, displaying the alert's content continuously [2]. Contrary to auditory and tactile alerts, visual alerts can manipulate salience through the use of hue, luminance, and size [1]. Auditory signals have the advantage of capturing immediate attention upon presentation. According to the multiple resource theory [3], auditory stimuli can be perceived with minimal interference to the manual driving task. Experimental research has shown that auditory stimuli elicit faster responses compared to visual stimuli, enabling quicker reactions to hazards [4]. Moreover, auditory alerts can provide better location information compared to tactile alerts [5, 6]. In driving situations, visual and auditory tasks are frequently secondary tasks, making tactile sensations less susceptible to distracting drivers [7]. Unlike visual stimuli, tactile alerts can be physically stimulated, allowing for quicker attention switching [8]. According to studies [9, 10], tactile stimuli are effective for forward collision warnings (FCW), and varying the intensity can convey meaningful degrees [11]. However, the dynamic character of driving can influence the effectiveness of warnings. Perception can be difficult if a stimulus requires the use of the same sensory organs for distinct tasks. A visually prominent alert on the in-vehicle human-machine interface (HMI) may go unnoticed if the driver is focused on their phone or the road ahead. Similarly, it can be challenging to perceive an auditory alert while engaged in a phone conversation. When the road surface is unstable or when the vehicle's vibrations are forceful, tactile alerts can be ignored. In addition, auditory alerts are dependent on time, so if one misses them, they must be repeated. If the working memory is engaged in a secondary task when a meaningful auditory signal, such as a word or sentence, is presented, the meaning of the auditory signal may not be comprehended due to limited cognitive resources [12]. Tactile notifications can provide stimulation, but it is more difficult to convey their meaning and orientation compared to auditory alerts [6]. Numerous studies have demonstrated the effectiveness of multimodal warnings in compensating for deficiencies and providing redundant information. Several studies have demonstrated that multimodal alerts decrease false positives [13, 14]. However, it is essential to keep in mind that humans have a limited capacity to divide their attention between two sensory channels. When two signals are simultaneously presented to distinct sensory channels, one may be ignored [15]. While this is acceptable if all cues presented at the same time have the same meaning, people are more likely to remember only one if they convey distinct information. The ability to divide attention across multimodal displays declines with age [16]. Accordingly, extensive research has been conducted on the advantages and disadvantages of multimodality, based on the degree of autonomy and the presence of dual tasks.

Numerous guidelines for in-vehicle visual, auditory, and tactile stimuli have been devised based on existing signal guidelines from human factors research [17-19]. Researchers have performed quantitative analyses to investigate the effects of signals on the human perceptual system, providing both general guidelines (e.g., salience, discrimination) and specific values for their contexts [17, 20]. Guidelines suggest that for visual display, the text should be at least 0.25 inches high [17]. Visual guidelines emphasize providing vital information in the driver's central field of vision, utilizing colors that correspond to the severity of a hazard, and modulating luminance to match driving conditions [1, 19]. Regarding auditory signals, various reports provide slightly divergent recommendations. Auditory tones should be approximately 15 to 30 dB above the masked threshold but should not exceed 115 to 120 dB in absolute amplitude [17, 18]. The frequency range for sound should be between 100 and 4000 Hz, audible between 50 and 90 dB, but not uncomfortable [17-19]. [18] suggests signal durations between 100 and 500 ms. A minimum of 80 dB in the 1-5 kHz frequency range has been suggested [21] for audible warning signals. In addition, it has been suggested that the duration of the warning should be shorter than the average response time expected. Another study found that a warning tone with a pulse rate greater than 6 Hz is perceived as more urgent than one with a pulse rate below 6 Hz [22]. Depending on the body part, tactile detection thresholds vary, with guidelines recommending that amplitudes be set at 15-20 dB above the detection threshold [23, 24]. Avoid amplitudes greater than 0.6-0.8 mm, as they may induce a painful sensation. The frequency of the tactile signal should be between 150 and 300 Hz, and the burst duration should be between 50 and 200 ms, as prolonged vibrations can be irritating [24]. These guidelines serve as the foundation for vehicle-driver interaction research and as suggestions for in-vehicle information systems.

2.2. Take Over Request and Modality

In the context of manual driving, warning signals indicate the likelihood of a collision with another object, taking lateral and longitudinal coordinates into account. The specifics of the signals can substantially affect the reaction time of the driver. In a study conducted by [20], the researchers manipulated factors such as signal loudness for auditory signals, signal amplitude for tactile signals, and signal size and luminance for visual signals in order to determine their effect on participants' reaction times. The study found a correlation between the frequency of tactile signals and the pitch of auditory signals and quicker reaction times [20]. Using this line of inquiry as a basis, [21] implemented a driving scenario involving participants and manipulated the warning signal characteristics to observe their responses. Their findings have been extensively cited as a standard in subsequent research. Consequently, the majority of research on signaling for takeover requests in the context of partially autonomous driving has focused on comparing various modalities using predefined stimuli or investigating the effects of multimodality.

Research on the modality of the takeover request (TOR) can be broadly divided into three categories. First, research has investigated the effect of distinct modalities on human perception in TOR

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situations [25]. For example, professional drivers have shown that a combination of forward collision and lane change warnings is appropriate for commercial motor vehicles. However, they exhibited typically negative responses to the use of haptic presentation modalities for warnings [26]. The second area of study investigates individual differences in objective or subjective responses to TOR signaling. This can be accomplished via surveys and experiments. Younger adults responded to auditory and tactile stimuli in TOR situations faster than older adults, according to one study [27]. In some instances, however, older drivers demonstrated response times comparable to those of younger drivers [28]. In addition, research indicates that older drivers tend to focus more on the road and less on secondary tasks [29]. The third area of study focuses on cross-modality comparisons. Similar to the cross-modality comparisons conducted in manual driving by researchers such as [7, 30], a number of studies [5, 14, 31, 32] have investigated which modality is more effective at triggering driver responses during control transitions in partial autonomy. However, these research occasionally produce contradictory results. Depending on variables such as secondary tasks or timing, some studies have found that tactile cues are more effective than auditory cues [31, 32], while others have found the opposite [5, 14].

Table 1. Warning signals used in previous research.

Author	signal[1]	visual stimuli	auditory stimuli	tactile stimuli	result[2]
[30]	V, A, T	5x5cm nine red LEDs, luminance 45.4cd/m^2	75dB 2000Hz	3 tactors (VBW32), 290Hz sinusoidal, amplitude 15μm	T > V
[7]	A, T		70dB 2000Hz	3 tactors (VBW32), 290Hz sinusoidal, sufficient intensity	T > A
[6]	A, T		105dB 2700Hz	3X2 tactors (PicoVibe), 60Hz	Multimodal > unimodal
[31]	A, T		60dB 1kHz	4 tactors (Vp216) 64Hz amplitude 10V	T > A
[32]	V,A,T	23 red LEDs, luminance 1.5 a.u. at 30mA, Brightness 45 lux	60-68dB (50-51dB)	150Hz sinusoidal, amplitude 18.8V	V, T > A
[14]	A, T		70dB 8000Hz	Butt Kicker Gamer 2	A > T
[33]	V, A, T	Three 5 mm LEDs 41-53lux	72dB(lateral) 79dB(center) 350Hz	two vibrationmotors 100-110Hz, Steering wheel	A, T > V
[29]	V, A, T	200 x 200 pixel, red circle	0~100dB, 400Hz	2 tactors 250Hz intensity 1-255 gain units	V, A conditions: younger adults had shorter response time than older adults

[5]	V, A, T	RGB LED strip	246, 750, 1250Hz	3x3 tactors (DC vibration motors with 12000rpm)	A > T

[1] V = visual, A = auditory, T = tactile, [2], A > B means that A resulted in a better participant response than B.

Each study's stimuli were generated by manipulating a number of variables, including pitch and loudness for auditory stimuli, amplitude and cycle for tactile stimuli, and luminance and size for visual stimuli. Such data are summarized in Table 1. An important question arises: Are differences in driver responses to stimuli across different modalities primarily influenced by the cognitive characteristics of individuals or by differences in stimulus characteristics? In the investigations [7] and [31], we discovered that tactile cues were more effective than auditory cues. However, according to studies [14] and [5], auditory cues are superior to tactile cues. Is this difference owing to the experiment's context or purpose? Or, is it possible to achieve various outcomes by altering the stimuli within the same context? It is possible that a small modification, such as increasing the auditory stimulus loudness by 10 dB, could eliminate the observed difference. Therefore, it is essential to precisely define the detailed characteristics of the stimuli used in the experiment and compare the effectiveness of each modality. However, addressing this issue in a single study is difficult because manipulating the signal at multiple levels complicates the experimental design, especially when manipulating other driving-related variables and secondary tasks. In addition, previous research on manual driving and warning signals has revealed that individual background factors affect not only driving behavior but also the perception of stimuli.

This requires research examining how the responses of individuals change when stimulus details are changed. In this study, we investigated how people's responses change when the detailed characteristics of stimuli change, concentrating on the visual, auditory, and tactile senses, which have been primarily manipulated in previous research, and how they differ across modalities. In addition, we sought to determine if there was an interaction between each modality and the demographic information (age, gender, etc.) of each participant.

2.3. Individual Differences in Driving

The influence of a personal background on driving task performance has been extensively studied, both in the context of manual driving and autonomous driving research. Age, gender, and experience are commonly investigated factors. These differences have been examined in various settings, ranging from laboratory-based signal detection studies to real-world driving tasks. As autonomous driving technology continues to evolve, considering the diverse characteristics of different individuals becomes increasingly important to create personalized vehicles. While it is not feasible to design warnings tailored to every individual difference or personal characteristic, it is feasible to include a representative sample of the target population when testing warnings [20].

A study by [34] examined individual differences in reaction time using a simple finger response task involving visual, auditory, and tactile stimuli. The findings indicated that responses to tactile stimuli were generally faster than visual and auditory stimuli, while auditory responses were faster than visual responses. In terms of age differences, reaction times for both visual and auditory stimuli tended to be slower with increasing age. Furthermore, women exhibited faster reaction times compared to men [35]. It has been observed that women have a higher sensitivity to sound, perceiving even small changes in decibel levels [35]. Brain activity measurements have also shown that women exhibit higher activation in the right prefrontal cortex in response to noise compared to men [36]. Additionally, women tend to excel in discriminating rhythm and pitch changes compared to men [36]. These individual differences may similarly manifest in the signals provided by vehicles, and gender differences may also exist in the level of auditory cues.

The number of older drivers aged over 65 years is getting increasing. Older drivers often rate their driving ability very highly, but actually, they suffer from a lot of cognitive function such as perception, attention and memory [27]. Also, older adults have a narrower visual field [38], become harder to detect high-frequency sounds [39], and are less sensitive to tactile cues [40]. They are more likely to experience a decline in cognitive function that can affect their ability to safe operate a motor vehicle and accident rates increase after age 65. In the [29], they used multiple visual, auditory, and tactile stimuli as TOR cues and found that younger adults had faster brake reaction times when using single visual and auditory stimuli compared to older adults. However, tactile signal did not make a difference.

previous research suggests that there are fundamental individual differences in how people respond to signals. Studies have explored individual differences in signal response during driving tasks, and guidelines for cues have provided a range of possibilities based on underlying cognition factors such as perception, cognition, and decision-making. However, these guidelines do not address the specific appropriateness of cues for each individual. In addition, studies focusing on TOR situations have typically examined combinations of modalities rather than different levels of stimuli, so it is unknown whether differences in response across modalities are due to cognitive differences or differences in stimulus details. Few studies have examined how manipulating sub-attribute of TOR signaling changes reaction times and whether there are interactions with personal background. Furthermore, these studies have been conducted in diverse simulation environments with different variables, such as secondary tasks, making it challenging to draw absolute comparisons unless different signals are compared within the same environment.

In our research, we presented participants with visual, auditory, and tactile signal with different combinations of sub-attributes in a TOR situation and examine their responses. We tried to verify if there is a correlation between personal background and modality and there are some signals that people respond better or worse according to age, gender, and driving style. Additionally, we wanted to examine how individual's responses vary with changes in sub-attributes of the signals. If participants' responses are linearly faster as the strength of the signal increases, then the strength of the signal would be an important factor to address in studies measuring reaction times for TOR. So, we investigated whether reaction times demonstrate a linear increase, a stepwise increase, or no significant difference beyond a certain level of signal strength. Furthermore, we assessed participants' subjective perceptions of noticeable, comfort, and suitable for each signal and compare these subjective evaluations with behavioral responses. In summary, our study seeks to validate the following research questions:

Research Question 1. Are there correlations between reaction times to visual, auditory, and tactile signals and personal background (gender, age, driving experience, etc.)?

Research Question 2. Are there differences in reaction times to visual, auditory, and tactile signals and their sub-attributes based on personal background?

Research Question 3. What is the relationship between subjective judgment of the signal and reaction time?

3. Materials and Methods

3.1. Participants

Participants were recruited from people with a driver's license between the ages of 20 and 70. A total of 101 participants were recruited in this experiment. Of these, two participants dropped out during the experiment, leaving 51 male and 48 female participants, with a mean age of 48.05 (SD = 15.00). We collected information on participants' driving experience, frequency of driving, number of accidents, driving safety, and driving speed. The demographics of the participants are presented in Table 2. This research was approved by the Stanford Institutional Review Board (No. 62510).

Table 2. Frequency analysis of demographic information.

Variable	Group	N	%
Gender	man	51	51.52
	woman	48	48.48

Variable	Group	N	%
Age	20s	16	16.2
	30s	21	21.2
	40s	18	18.2
	50s	20	20.2
	60s	18	18.2
	70s	6	6.1
Driving Experience	< 1 year	12	12.1
	1-3 years	7	7.1
	3~5 years	7	7.1
	5~10 years	16	16.2
	> 10 years	57	57.6
Driving Frequency (week)	< 1 hour	22	22.2
	1-5 hours	25	25.3
	5-10 hours	32	32.3
	10~20 hours	13	13.1
	< 20 hours	7	7.1
Number of Accident	0	76	76.8
	1	13	13.1
	2	8	8.1
	3	2	2
Driving Stability	very stable	1	.99
	generally stable	32	31.68
	slightly stable	14	13.86
	moderate	19	18.81
	slightly aggressive	21	20.79
	generally aggressive	2	1.98
	very aggressive	0	0
Driving Speed	very slow	1	.99
	generally slow	10	9.90
	slightly slow	34	33.66
	Moderate	37	36.63
	slightly fast	34	33.66
	generally fast	9	8.91
	very fast	0	0

3.2. Apparatus

For the experiment, we set up a driving simulation environment and informed participants that they were driving a vehicle in a partially autonomous environment. For this purpose, INNO Simulation Company (Seoul, South Korea) built an environment at the research center that shows the driving situation on a 180-degree screen, creates a real driver's seat, and enables real-time simulation. Since the purpose of the experiment is to understand the driver's reaction when the vehicle is driving and giving signals to the driver, rather than the driver's actual driving, we did not use a simulation video. Instead, we used a video recording of actual driving scenes. As shown in Figure 1, the driver's seat was equipped with a speedometer and an in-vehicle display (center fascia) on the driver's right side. The speedometer was programmed to present visual stimuli, and the center fascia was designed for post-experiment surveys.

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Figure 1. Driving scene used in experiment.

3.3. Stimulus

To use it as a TOR signal, we prepared visual, auditory, and tactile stimuli. In previous research, we find that auditory stimuli are likely to modify using pitch and loudness, but visual and tactile stimuli vary widely in terms of the size of the physical interface provided, manipulation methods, and units. For the purpose of this study, visual stimuli were created with four different levels of brightness and size, and auditory stimuli were created with four different levels of pitch and loudness, the same as in previous studies. Tactile stimuli were created with four levels of amplitude and frequency. First, the value (V) of HSV (Hue, Saturation, Value) was adjusted to manipulate the brightness of the visual stimuli. The V of the dashboard background was set to 0, and the circle stimuli were presented with V of 15, 95, 175, and 255 to manipulate brightness. The size of the circle stimuli was manipulated by varying the radius in pixels to 27, 57, 120, and 252, as shown in Figure 2. The pitch of the auditory stimuli was 500, 1000, 2000, 4000 Hz and the loudness was 50, 60, 70, 80 dB, within the guidelines of [19, 21]. The noise level in the room where participants conducted the experiment was 50 dB. Each sublevel of each auditory stimulus was combined to create a total of 16 auditory stimuli, and all auditory stimuli used in the experiment are included in the Supplementary Material. The tactile stimuli were created by creating a structure inside the driver's seat that could be acoustically vibrated to present stimuli to the back and buttocks. Using the VM-6360 (Hong Kong, China), which can measure the magnitude of vibration, we created vibration stimuli with peak amplitudes of 1, 4, 8, and 12 v, and frequencies of 25, 50, 200, and 400 Hz. Video clips of the driving environment were created by the experimenter over several days of driving and edited to fit the experiment.

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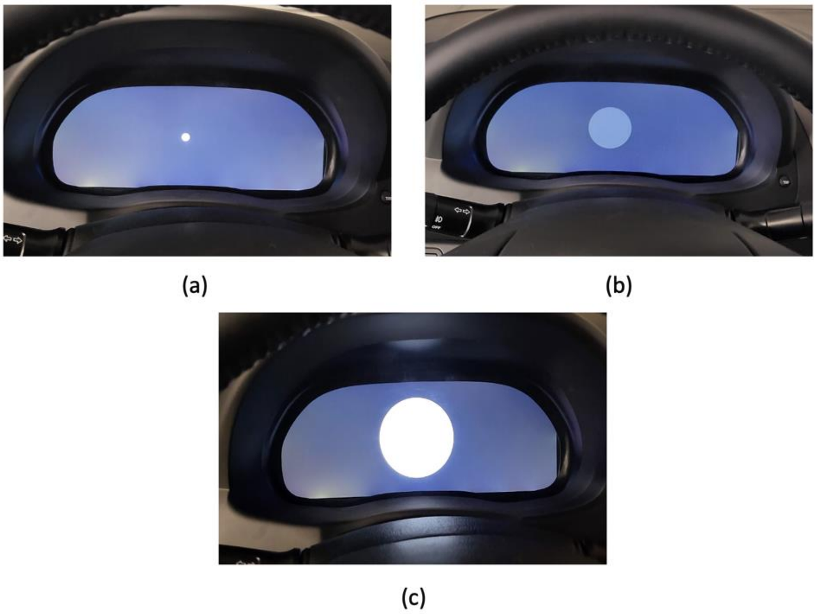

Figure 2. visual stimuli used in experiment: (**a**) lowest size(27px) + highest brightness (V175); (**b**) 2nd highest size (120px) + lowest brightness (V15); (**c**) highest size (252px) + highest brightness (V175); V indicates Value of HSV.

3.4. Procedure

The experiment was conducted in a laboratory containing a driving simulator. An experimenter provided participants with a comprehensive explanation of the entire experiment procedure. After granting their consent to participate, participants sat in the driver's seat and made any necessary adjustments for comfort. The experimenter provided participants with detailed instructions regarding the driving simulator and took them on a practice drive to familiarize them with the procedure. During the course of the study, participants were informed that they were in a partially autonomous vehicle that was currently driving. The participants were instructed to experience driving without operating the steering wheel or pedals, and they were free to observe their surroundings.

Then, participants completed a total of three blocks of experiments during the experiment trial. Each block presented a different stimulus modality, and participants were randomly asked to respond two to three times per minute while viewing a driving video. In order to prevent participants from anticipating the timing of the stimuli, false alarm trials were included. Participants were given a break between each segment before moving on to the next.

After participants completed the three blocks of video-based trials, the driving video was removed and they were presented with the stimuli in pairs. The participants were then asked to indicate which cues they found more comfortable, suitable, and easily noticeable in a situation involving partially autonomous driving. This procedure was repeated for each modality, yielding three blocks of pairwise comparisons. Two sub-attributes of the same modality were manipulated within each block. In the pitch manipulation condition, for instance, the loudness was maintained at 70 dB, and pitch comparisons were made between frequencies such as 500 Hz versus 1000 Hz, 500 Hz versus 2000 Hz, etc. Each block consisted of pairwise comparisons of the same modality, for a total of 12 comparisons. Overall, 36 comparison pairs were produced. Upon completion of all comparisons, participants were asked to complete a questionnaire in Appendix A regarding their individual background (e.g., gender, age, driving experience, frequency of accidents, driving stability, driving speed). The experiment was then concluded. The duration of the overall experiment was approximately one hour.

3.5. Analysis

We performed an analysis to investigate how responses to takeover requests varied depending on the level of sub-attributes within each modality and participants' personal backgrounds. The dependent variable was the reaction time taken by participants to press the pedal after the cue was presented. We categorized "no response" when participants did not respond to the cue for more than 5 seconds after its presentation. To begin, we conducted a correlation analysis to examine any relationships between participants' personal backgrounds and the sub-attributes within each modality. Subsequently, we conducted a repeated measures analysis of variance (RM ANOVA) to explore the interaction between participants' personal backgrounds, the three modalities, and the sub-attributes. Participants' personal backgrounds were treated as a between-participants variable, while the modality sub-attributes were considered within-participants variables. Finally, we analyzed the ratings of comfortability, noticeability, and suitability for the cues using a paired comparison analysis [41]. This analysis allowed us to assess how the ratings varied based on participants' personal backgrounds.

4. Results

4.1. Correlation Analysis

Table 3. The result of correlation analysis.

Response time	Auditory	Tactile	Visual
Age	**.44****	**.42****	-.05
Gender	-.17	-.16	-.17
Experience	.10	.12	.10
Frequency	.15	.14	**.21***
Accident	.02	-.02	.07
Driving style	.14	.11	-.01
Driving speed	.08	.03	.14

*p < .05, **p < .01

To examine the correlation of TOR reaction time with individual background and modality, Pearson correlation analysis was performed. The results are presented in Table 3. Age was positively correlated with auditory (r = .44) and tactile (r = .42). As age increases, reaction times to auditory and tactile cues increase. However, for visual cues, there was no correlation with age. The visual cue was correlated with driving frequency (r = .21). This indicates that the higher the frequency of driving per week, the higher the reaction time to visual cues. Next, we conducted a Pearson correlation analysis with individual background by level of each modality's sub-attribute (tactile: amplitude, frequency; auditory: pitch, loudness; visual: size, brightness). The results are presented in Appendix B.

The personal background that correlated most strongly with the sub-attribute was age. For all the tactile and auditory sub-attributes, we saw an increase in reaction time as age increased. Gender correlated with some of the sub-attributes for both tactile and auditory, particularly for auditory, where women had faster reaction times than men for stimuli at 70 and 80dB. Women also had faster reaction times to stimuli at 4000 Hz than men. Driving frequency, number of accidents, and driving speed were also correlated with sub-attributes of visual stimuli. In particular, the number of accidents was correlated with the smallest and second smallest visual stimuli. In other words, the more accidents a driver had, the slower they responded to the smaller visual stimuli.

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4.2. Interaction effects between individual background and modalities

To examine the interaction of personal background and modality, we conducted a RM ANOVA for modality and each signal's sub-attributes. We first calculated the overall mean reaction time per modality without considering the sub-attribute of each modality to extract the mean reaction time for visual, auditory, and tactile. Next, we analyzed the interaction of each individual background and the three modalities on reaction time. We also recoded age into 20-30s, 40-50s, and over 60. We then analyzed how each individual background and the three modalities interacted with their reaction times. The interaction between age and modality was significant, $F(4, 192) = 8.82$, $p < .001$, $\eta_p^2 = .16$, with little difference between ages for visual stimuli, but significant increases in reaction time with age for auditory and tactile stimuli (Figure 3a). All other interactions effects between individual background and modality were not significant.

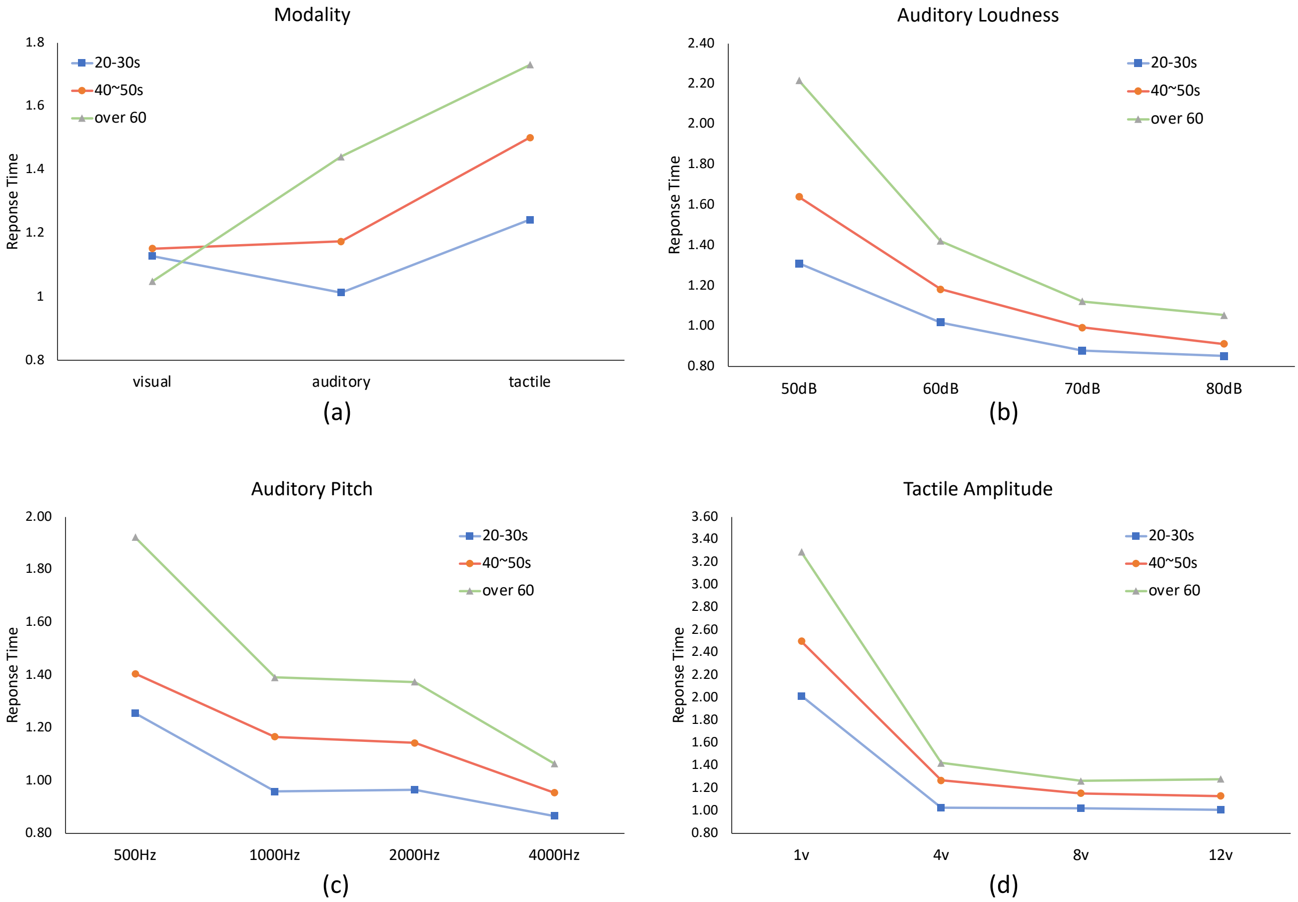

Figure 3. Interaction effect of the experiment: (**a**) Interaction effect between age and modality; (**b**) Interaction effect between auditory loudness and age; (**c**) Interaction effect between auditory pitch and age; (**d**) Interaction effect between tactile amplitude and age

Next, we analyzed interaction effects between the level of each modality sub-attribute and personal background. Similar to before, we found interactions between age and amplitude for tactile, $F(6, 282) = 4.94$, $p < .001$, $\eta_p^2 = .10$, loudness for auditory, $F(6, 282) = 10.70$, $p < .001$, $\eta_p^2 = .19$, and pitch for auditory, $F(6, 282) = 4.63$, $p < .001$, $\eta_p^2 = .09$, respectively. We found that age differences were most pronounced at the lowest levels of tactile amplitude and auditory loudness and pitch (Figure 3b-d). There were no differences based on other individual backgrounds.

To investigate how participants' reaction times changed as the strength of each signal's sub-attributes varied, we analyzed main effects of sub-attributes. These analyses aimed to identify any trend lines or patterns in participants' reaction times corresponding to changes in the strength of the sub-attributes within each signal. For all sub-attributes, the main effect of sub-attributes level was significant at the .05 level of significance. To determine if this main effect was due to the lowest level

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of each stimulus sub-attribute, we excluded the lowest level and conducted a repeated measures ANOVA on the remaining three levels, and found that there was still a significant difference at the .05 level of significance. We found that TOR reaction time decreased as each modalities' sub-attribute level increased (e.g., tactile amplitude increased, auditory pitch increased, visual size increased, etc.; Figure 4a-c).

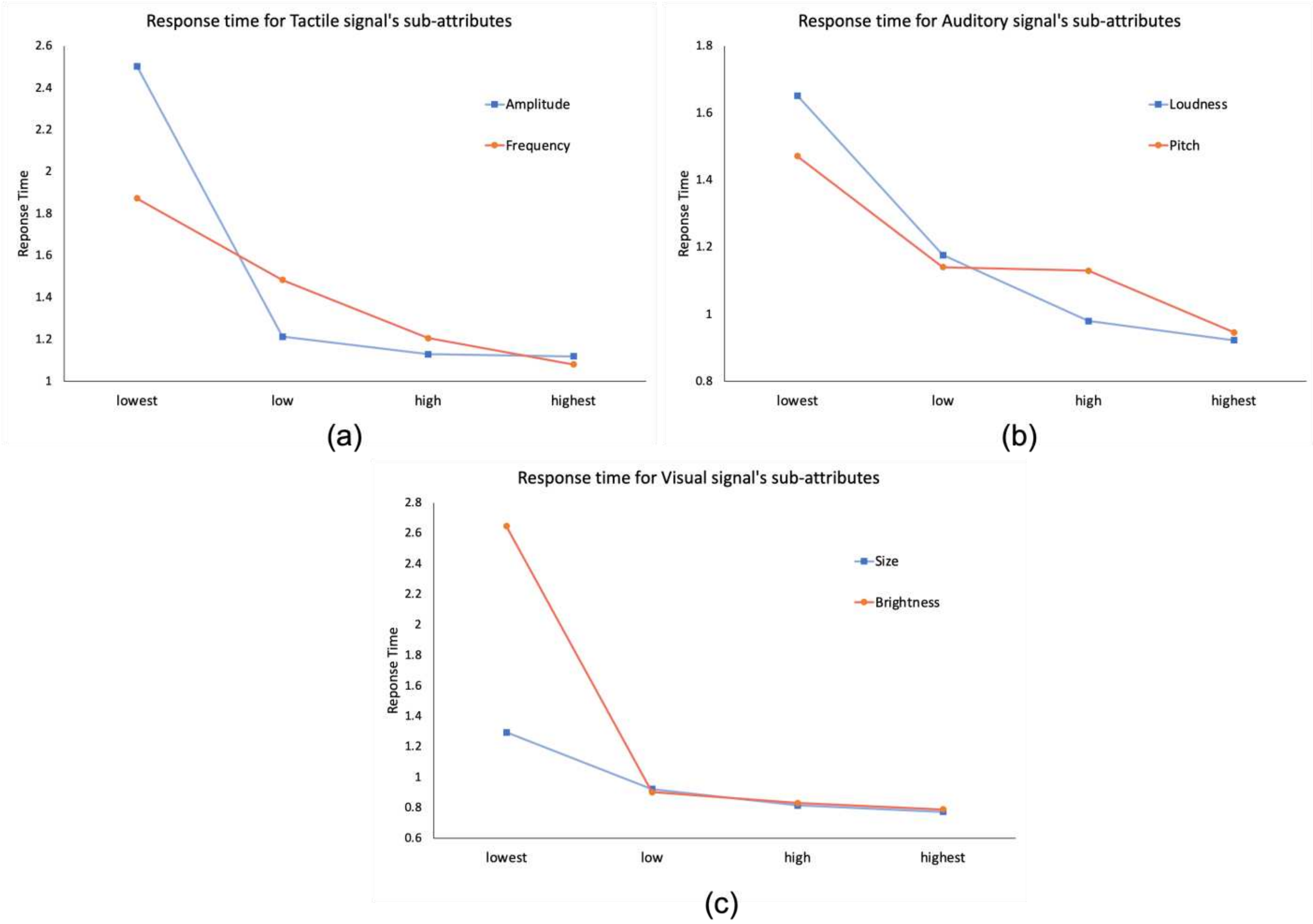

Figure 4. Main effects of each signal's sub-attributes on TOR response time: (**a**) Main effects of tactile signal's sub-attributes; (**b**) Main effects of auditory signal's sub-attributes; (**c**) Main effects of visual signal's sub-attributes; x-axis indicates intensity of signal.

To further examine the main effects identified in our study, we conducted post-hoc tests using the Bonferroni method. These tests allowed us to make pairwise comparisons between different levels of the signal sub-attributes within each main effect to determine specific differences in participants' reaction times. The post-hoc tests using the Bonferroni method revealed significant differences between all conditions (lowest to highest intensity) for both frequency in tactile signals and loudness in auditory signals. These differences were significant at the 0.001 level of significance. This indicates that participants' reaction times show continuously changes as the signal become louder or the vibration frequency increased. There were no significant difference in the amplitude of the tactile signal between the 8v and 12v and pitch of the auditory signal between the 1000Hz and 2000Hz. For visual signals, we found no differences except between the lowest intensity and others.

4.3. Subjective Preferences for Signals

For each modality, we measured the extent to which participants subjectively rated the modality as noticeable (easy to awareness), comfortable, and suitable as (appropriate to use) a TOR signal. This was accomplished by utilizing paired comparison analysis, where the frequency of the signal selected

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as the better of the comparison pair based on each person's response was added together and converted to a percentage. Tables and graphs of all results are available in the Supplementary Material. Regarding auditory signals, participants rated the 80dB intensity level as easy to awareness. However, they perceived it as less comfortable and less appropriate to use as a signal compared to the 70dB intensity level. In terms of pitch, participants rated the 4000Hz as easy to perceive. However, they found it less comfortable and less appropriate to use as a TOR signal compared to the 1000Hz and 2000Hz. In the case of tactile signals, participants evaluated that higher amplitudes and frequencies were perceived as more noticeable, comfortable, and appropriate to use as TOR signals. Regarding visual stimuli, participants rated larger visual signal as better in terms of noticeability, comfort, and appropriateness to use. However, in terms of brightness, the brightest stimuli were rated as less comfortable and less appropriate to use as TOR cues. Additionally, in terms of individual difference, older people reported being less comfortable with smaller vibrations than other age groups (Figure 5b). For pitch of auditory signal, we found a trend toward rating higher pitches as more comfortable and more suitable as TOR signals as age increased (Figure 5a).

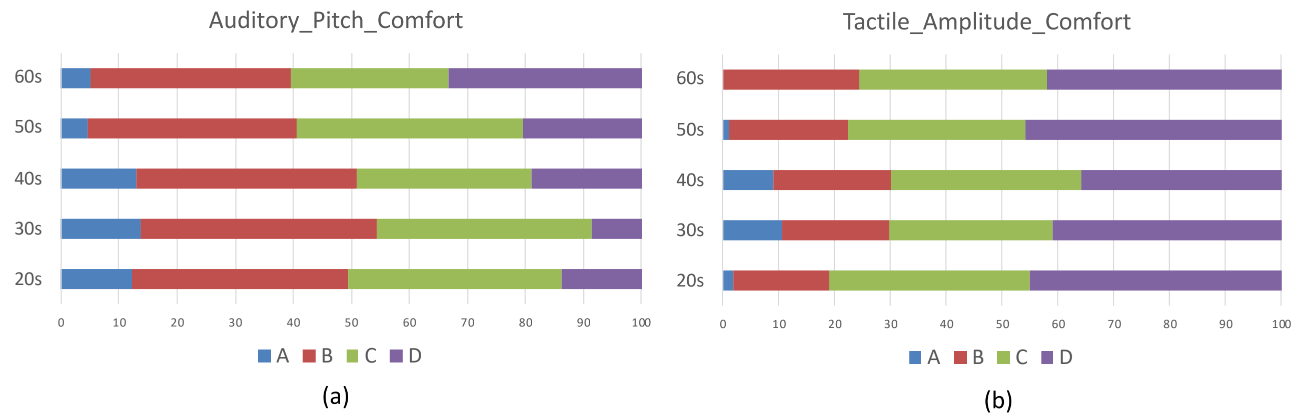

Figure 5. The result of paired comparison analysis for age: (**a**) Participants' responses to how comfortable they were hearing each auditory cue based on their age, A= 500Hz, B = 1000Hz, C = 2000Hz, D = 4000Hz; (**b**) Participants' responses to how comfortable they were feeling each tactile cue based on their age, A = 1v, B = 4v, C = 8v, D = 12v; y-axis indicates ages.

5. Discussion

This study aimed to determine how changes in sub-attribute for each modality and personal background affect TOR responses in partially autonomous driving situations. For this purpose, correlation analysis, repeated measure ANOVA, and paired comparison analysis were conducted, and the results are summarized below according to research questions.

Research Question 1 focused on examining correlations between reaction times to visual, auditory, and tactile signals and participants' personal backgrounds. Our findings revealed significant correlations between individual background factors and TOR signaling modalities and sub-attributes. Specifically, women responded faster than men to larger auditory stimuli and faster to higher pitch. Reaction times for both auditory and tactile modalities also increased with age. These results can be seen in more detail in the interaction between age and modality in research question 2.

Research Question 2 aimed to determine if there were differences in reaction times to visual, auditory, and tactile signals and their sub-attributes based on participants' personal backgrounds. In terms of visual stimuli, we found minimal age differences. However, for auditory and tactile signals, reaction times increased with age. Notably, the age differences were most pronounced when the amplitude of the tactile stimulus, as well as the loudness and pitch of the auditory stimuli, were at their lowest intensity levels. Furthermore, each sub-attribute exhibited a distinct pattern of faster response times as intensity increased. Specifically, we observed a continuous decrease in reaction times with every 10dB increase in auditory loudness between 50 and 80dB. Similarly, as the frequency of

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vibration increased from 25 to 50, 200, and 400Hz, participants' reaction times continued to decrease. Interestingly, we found no significant difference in reaction times between 1000 Hz and 2000 Hz for the pitch of the auditory signal. However, a decrease in reaction time was observed at 4000 Hz. Additionally, no significant difference was found in reaction times between 8v and 12v for the amplitude of the tactile signal.

These results carry significant implications for future TOR studies. While the criteria for selecting signal intensity in TOR studies may present some ambiguity, our findings highlight the crucial role of signal intensity in influencing participants' reaction times. It is important for researchers to carefully select an appropriate level of signal intensity, considering previous studies conducted in similar settings. Furthermore, while auditory signals are relatively well-characterized in terms of pitch and loudness, the same level of detailed characterization is lacking for visual and tactile signals. Consequently, researchers should strive to provide comprehensive descriptions of the signals used in their studies.

In Research Question 3, our aim was to explore the relationship between participants' behavioral responses and their subjective evaluations of signals. Participants were asked to rate which signals they found more noticeable, comfortable, and appropriate to use. The results indicated that the ratings were influenced by the intensity levels of the signal's sub-attributes. The lower the intensity of a signal's sub-attributes, the more negative people rated it. However, for the pitch and loudness of auditory signals and the brightness of visual signals, people preferred the signal with the next lower intensity to the highest intensity. If the TOR situation is very urgent and life-threatening, the stimulus that will elicit the fastest response should be used, regardless of how people evaluate it [1]. However, in a TOR situation, what is important is not only to alert people but also to help them make accurate situation awareness [42], so a stimulus that is more interactive than one that may cause irritation or narrowing of attention may be appropriate.

Subjective ratings also show that older adults are less comfortable with lower pitch stimuli and more comfortable with higher pitch stimuli than other age groups. This is likely related to the cognitive decline that occurs with increasing age [39,40]. However, we still found that older people had similar reaction times to visual signals. Although the visual field narrows with age [38], the reaction time to signals is most effective with visual signals in this study. This may be because the design of the study did not allow for other secondary tasks or environmental factors that could have influenced the participants. However, the faster reaction times for visual stimuli compared to other auditory and tactile stimuli suggest that the effectiveness of visual stimuli should be considered when selecting TOR stimuli for older adults. The implication of this study is that we studied the three types of modalities used for TOR by varying the detailed sub-attributes in more depth. The results of this study, which examined how reaction time changes as the detailed attributes change and whether there is an interaction between the changes in detailed attributes and individual background, can be used as a reference for future TOR signals and are expected to serve as a bridge to further research on individual differences.

Despite the valuable insights gained from this study, there are several limitations: Firstly, this study employed arbitrary categories for signal sub-attributes instead of examining them on a continuum. This limited our analysis to verify precise trends in participants' reaction times as a intensity of specific signal's sub-attributes. Future research could overcome this limitation by implementing a method that allows for a more elaborated exploration of reaction times across a continuum of signal levels.

Secondly, the study's examination of personal backgrounds was limited in scope. The duration of the driving simulator experiment and signal evaluation made it hard to add a wider range of driving-related personal backgrounds. Future research should consider incorporating additional personal background variables, such as trust in technology and risk-taking propensity. Additionally, obtaining data on participants' driving behavior directly through the driving simulator could provide further insights into how personal backgrounds relate to driving performance and TOR responses.

It is important for future studies to address these limitations to gain a more comprehensive understanding of the relationship between signal, individual differences, and TOR responses in partially autonomous driving situations. By incorporating a continuum of signal levels and considering a broader range of personal backgrounds, researchers can further enhance the validity and applicability of their findings.

6. Conclusions

This study investigated the visual, auditory, and tactile signals that can be used in TOR situations during partial autonomous driving to find how people's reaction time varies with changes in various signal sub-attributes. While research on in-vehicle signaling and human responses in the context of autonomous driving has been vibrant, there is still a need for fundamental and basic research to provide a solid foundation for current studies. The existing research has largely focused on exploring the interaction of various environmental variables and their impact on human responses. However, there is a gap in understanding the core principles underlying these responses.

This study contributes to filling that gap by investigating the effects of sub-attributes of TOR signaling modalities and individual background factors on reaction times and subjective evaluations. By examining these fundamental aspects, we can establish a stronger and more comprehensive understanding of the dynamics between stimulus characteristics, individual differences, and TOR responses in partially autonomous driving situations. The findings of this study serve as pillars that support the current research in the field and provide valuable insights that can contribute to the development of more consistent interpretations of results in future studies. By conducting more basic research, we can strengthen the theoretical foundations of in-vehicle signaling and enhance the effectiveness and design of autonomous driving systems.

In conclusion, this study underscores the importance of conducting fundamental research in order to advance our understanding of the interactions between autonomous vehicles and humans. By building a strong foundation of knowledge, future research can make more informed and meaningful contributions to the field, leading to improved safety, performance, and user satisfaction in autonomous driving environments.

Supplementary Materials: The following supporting information can be downloaded at: https://drive.google.com/file/d/1R2IwjNw6zxIaUz4saR6gNNvERTV_tgji/view?usp=sharing.

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Data Availability Statement: The data presented in this study are available on request.

Conflicts of Interest: The authors declare no conflict of interest.

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Appendix A

Table A1. Questionnaire to get individual backgrounds.

Individual background	question	scale
Age	What is your age?	Open-ended question
Gender	What is your gender?	Multiple choice questions
Experience	How long have you been driving?	Multiple choice questions
Frequency	How often do you drive per week?	Multiple choice questions
Number of Accident	How many accidents have you had?	Open-ended question
Driving Style	Please rate your usual driving style.	7-point Likert scale
Driving Speed	Please rate your usual driving speed.	7-point Likert scale

Appendix B

Table B1. Correlation analysis between modality sub-attributes and individual backgrounds.

		Age	Gender	Exp	Freq	Accident	Driving style	Driving speed
Tactile	Amplitude 1	.36**	-.09	.08	.08	-.06	.10	.02
	Amplitude 4	.41**	-.21*	.06	.14	-.02	.04	.01
	Amplitude 8	.34**	-.16	.06	.15	.05	.04	-.02
	Amplitude 12	.33**	-.14	.06	.11	.00	.10	-.02
	Frequency 25	.32**	-.12	.16	.13	-.07	.10	.06
	Frequency 50	.32**	-.15	.15	.19	.09	.15	.09
	Frequency 200	.44**	-.21*	.14	.17	.03	.12	.02
	Frequency 400	.39**	-.17	.01	.08	.03	.01	-.10
Auditory	loudness 50	.46**	-.08	.08	.10	-.03	.11	.03
	loudness 60	.45**	-.16	.12	.13	-.01	.12	.11
	loudness 70	.33**	-.24*	.07	.13	.07	.10	.09
	loudness 80	.28**	-.23*	.07	.20	.10	.18	.09
	Pitch 500	.38**	-.07	.07	.11	.03	.14	.03
	Pitch 1000	.43**	-.16	.11	.18	.02	.13	.14
	Pitch 2000	.41**	-.20	.09	.08	-.02	.10	.04
	Pitch 4000	.28**	-.23*	.09	.17	.07	.13	.09
Visual	size 27	-.10	-.15	.13	.14	.23*	-.07	.17
	size 57	-.19	-.06	.09	.17	.30**	.11	.16
	size 120	.02	-.07	.17	.10	.09	.04	.14
	size 252	.06	-.10	.23*	.12	.09	.02	.12
	brightness 15	.02	-.13	-.02	.14	-.14	.03	-.02

brightness 95	.05	.05	.08	.11	-.07	-.16	.06
brightness 175	-.10	-.12	.02	.01	-.06	.00	.16
brightness 255	.10	-.10	.12	.21*	.21*	.14	.24*

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