Age-Related Physical and Emotional Characteristics to Safety Warning Sounds: Design Guidelines for Intelligent Vehicles

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***Abstract*—Recent technological advances have made motor vehicles more intelligent to increase safety and comfort. An intelligent vehicle provides drivers with safety warning information through audible sounds, visual displays, and tactile feedback. However, elderly drivers often have decreased cognitive and psychomotor abilities in the areas such as hearing, eyesight, short-term memory, and spatial perception. Therefore, possible age-related deficits should be considered when designing effective warning systems. This paper evaluates the impact of advancing age on drivers' physical responses and emotional preferences with regard to audible safety warnings that are widely used to warn about driving hazards. Three sound characteristics (frequency, tempo, and intensity) and three age groups (younger, middle, and older) were considered in investigating the effect of age-related hearing loss and reduced speed of movement. Data were collected from 38 drivers who drove on a simulated rural road in a driving simulator. Experimental results showed that age influenced drivers' responses and emotional preference. An appropriate range of warning sounds is suggested.**

***Index Terms*—Advanced driver assistance system (ADAS), emotional preference, hearing, intelligent vehicle, older driver, physical response, safety warning sounds guideline.**

I. Introduction

Interest has recently focused on intelligent vehicles that offer a significant enhancement of safety and convenience to drivers and passengers [1]–[3]. As a component of an intelligent vehicle system, advanced driver assistance systems (ADAS), which assist in safe driving, are being developed [3]–[6]. ADAS components include adaptive cruise control (ACC) to reduce the speed and warn the driver when the car is about to crash (see Fig. 1), and the lane departure warning system (LDWS) to keep the car inside the line and warn the driver when the car is crossing a line. In addition, blind spot detection (BSD) and the rear detection system (RDS) provide information about blind spots and the rear of the vehicle, respectively [7]. ADAS sense the situation around the car in real time using vision and distance sensors (radar), and they warn the driver and control some car functions to prevent accidents [4]. In particular, ADAS provide auditory and visual warnings to the driver in the case of danger, and new technology has led to tactile warnings and the combination of two or more types of warnings [8].

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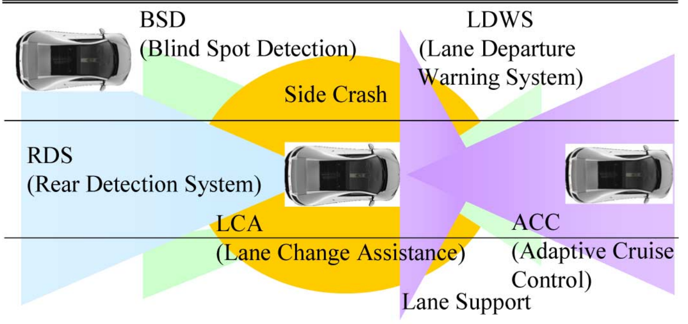

Fig. 1. Advanced Driver Assistance System for intelligent vehicles.

Numerous studies related to auditory warnings have been conducted. Keithley *et al.* [9] and Bielefeld *et al.* [10] researched about the age-related hearing and assessed hearing loss. Judy *et al.* [11], Belz *et al.* [12], and Graham [13] sought ways of designing effective auditory warning systems, such as the auditory icon, and assessed their efficiency. As well as research into visual and auditory warnings, assessments of the warning capability of each visual and auditory method were conducted by Rodway [14] and Chan [15]–[17]. In addition, Cummings *et al.* [18] assessed the recognition differences between single and multiple auditory warnings. Automobile companies have also investigated whether drivers recognize warnings better when tactile feedback is combined with auditory and visual methods [8].

However, additional research is required into the design of new safety warning sounds to work with previous ones because existing studies targeted the average driver, even though most owners of high-end cars with high-technology ADAS functions are older drivers [19]–[21]. In particular, many older drivers suffer from age-related hearing loss and tend not to cope well with dangerous situations like head-on collisions or lane deviations because they do not hear the warning sounds [22]. Moreover, existing studies of warning sounds assessed them only based on the physical response of drivers, neglecting the emotional preference [23]. Thus, some warning sounds may trigger negative emotions and lead to delayed driver response in case of danger.

This paper describes the characteristic of drivers to warning sounds based on their age and their emotional preference in a simulated driving situation to suggest a range of appropriate warning sounds. The assessment of physical response was based on elapsed times for acceleration release and for brake response. These dependent variables were examined for differences due to the frequency, tempo, and intensity of safety warning sounds. The emotional preferences of drivers were assessed based on perceived danger level and driver preference. These variables were assessed for differences due to the frequency, tempo, and intensity of safety warning sounds.

The rest of this paper is organized as follows. Section II introduces the experimental procedures used to assess the physical and emotional characteristics of drivers to safety warning sounds. Section III discusses the results of the experiments. Section IV provides conclusions and makes suggestions for further research.

TABLE I

Details of Experiment Participants

Age range	Number	Average age and SD (yr)	Driving record and SD (yr)
20s	12	25.0 (1.86)	4.83 (1.64)
40s	11	44.3 (2.41)	17.9 (5.80)
60s	15	63.9 (2.87)	28.3 (6.77)

Fig. 2. DGIST driving simulator.

II. Experimental Method

A. Participants

This study involved 38 participants recruited to analyze the physical and emotional characteristics of older people to safety warning sounds. Table I shows the age distribution of the participants. Because hearing loss is not gender specific, all the participants were male [22] and selection was limited to those who drove more than twice a week, had more than three years of driving experience, and had driven more than 30 000 km. The participants selected were sufficiently healthy to drive more than 3 h at a time and were free of mental illness and ear diseases such as tympanitis. The participants were paid for their participation; those in their twenties received 40 000 KRW (33 USD), and the others received 50 000KRW (42 USD).

B. Driving Simulator

This study involved an experiment using a driving simulator (see Fig. 2) at the Daegu Gyeongbuk Institute of Science and Technology (DGIST, Korea) to analyze the physical and emotional characteristic of older drivers to safety warning sounds. The driving simulator consisted of a digital projector, a 2400 $\times$ 1800-mm screen, PC controller, and a vehicle (Smart, Mercedes Benz). The software used in the experiment was STISM Drive (Systems Technology, Inc.), which provided pictures of the road and the car 20–30 times each second at a resolution of 1024 $\times$ 768 pixels. The simulators also provided kinetic feedback through a steering wheel with force feedback. The simulator included an encoder on the accelerator and brake pedals to measure the times taken to push or release each pedal. The program measuring the response time was developed using Labview 8.6 (National Instruments), and the signals from encoders were obtained using a USB-6008 DAQ digital acquisition system (National Instruments).

TABLE II

Self-Reported Items Used for Emotional Preference

Categories	Question wording
Preference	How would you describe your level of preference to hear warning sound? (1)very dislikeable (2) dislikeable (3) little dislikeable (4) fair (5) little preferred (6) preferred (7) very preferred
Perceived danger	How would you describe your level of perceived danger to hear warning sound? (1)very safe, (2) safe (3) little safe (4) fair (5) little dangerous (6) dangerous (7) very dangerous

C. Safety Warning Sounds

Sounds based on the LDWS warning sound of the Hyundai model “E” car were used to analyze the physical and emotional characteristic of older drivers to safety warning sounds. The basic LDWS 1.2-kHz warning sound was repeated every 800 ms. The major independent variables used in the experiment were selected based on relevant international standards and the opinions of an otorhinolaryngologist and professional musicians. The warning sounds used in the experiments had various frequencies (0.5, 0.75, 1.0, 1.5, 2.0, 3.0, and 4 kHz), tempos (200, 300, 400, 500, and 1000 ms), and intensities (75 and 85 dB, respectively). Seventy warning sounds combined with various frequencies, tempos, and intensities were created by sound experts and they occurred with random for counterbalancing in the experiment. Moreover, the warning sounds were checked and readjusted during the experiments using sound analysis software to tailor them to the environment and to the speaker being used.

D. Physical Response Assessment

The accelerator response time and brake response time of the drivers were measured for each age group and examined for relationships to the frequency, tempo, and intensity of the safety warning sounds. The accelerator response time was defined as the time from the moment when warning sound went off to the time that driver started to release the accelerator. The brake response time was defined as the time from the moment when driver released the accelerator to the time the driver applied the brake at least 10%. The response assessment experiment had participants push the accelerator to the floor and drive on a straight road, and then release the accelerator and apply the brake when the warning sound occurred at two types of random table. Participants had a 5-min break between experiments to reduce fatigue accumulation.

E. Emotional Characteristic Assessment

The drivers’ preference and perceived level of danger were measured for each age group according to the frequency, tempo, and intensity of the safety warning sounds. Each participant was presented with various warnings and asked to rate their level of preference and perception of danger for each warning. Question wording and response examples used in this analysis were described in Table II. The emotional characteristic assessment was conducted in the same environment (i.e., in the driving simulator) as the physical characteristic assessment with the driving simulator on autopilot mode. The participants were asked to listen to warning sounds for 10 s and score their preference and perceived level of danger. Each participant had a 5-min break between tests to reduce fatigue accumulation (see Fig. 3).

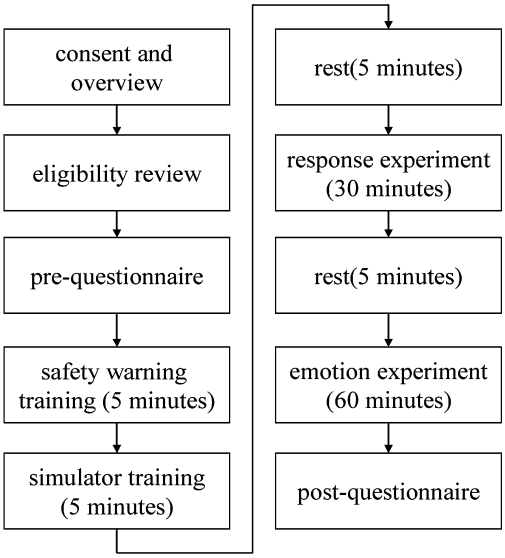

Fig. 3. Experimental procedure sequence.

F. Procedure

Fig. 3 describes the experimental procedure designed to analyze the physical and emotional characteristics of older drivers. The experiment had three phases: before, during, and after driving. The 30-min phase before driving consisted of obtaining consent, presenting an overview, reviewing the subject's eligibility, administering a preliminary questionnaire, and providing training on safety and the vehicle simulator. The driving phase in the simulator consisted of the response and emotion experiments, with a 5-min break between two. The response assessment took about 30 min, and the emotion assessment took about 60 min. The phase after driving was composed of a 10-min questionnaire about the subject's mental state and stress level. The complete experiment thus required about three hours per subject.

G. Data Analysis

The data were analyzed using version 14 of the SPSS statistical analysis software package (SPSS Inc.). Age, frequency, tempo, and intensity were the independent variables for the analysis of reciprocal actions. The dependent measures of physical response were comprised of the accelerator and brake response times, and emotional preference measures were comprised of subjective assessments of preference and perception of danger. The level of statistical significance was set at $\alpha = 0.05$.

III. Results and Discussion

A. Physical Characteristics

Fig. 4 shows the pure tone audiogram result of age groups. This experiment was conducted at the Daegu Fatima Hospital to measure participants' age-related hearing loss. The decrement of older participants' hearing ability is observed from 1 to 8 kHz as shown in Fig. 4. Due to the age-related hearing loss, the hearing threshold of older drivers was 1.94 times bigger than that of drivers in their twenties (minimum difference of 1.21 times at 0.5 kHz, maximum of 2.84 times at 4 kHz) and it was 1.58 times bigger than that of drivers in their forties (minimum difference of 1.19 times at 0.5 kHz, maximum of 2.09 times at 4 kHz) [22].

The accelerator response time results showed a statistically significant effect of age ($F(2, 1645) = 290.246$, $p = 0.00$), frequency ($F(6, 1645) = 16.535$, $p = 0.00$), tempo ($F(4, 1645) = 14.373$, $p = 0.02$), intensity ($F(1, 1645) = 23.637$, $p = 0.00$), and frequency $\times$ tempo ($F(18, 1645) = 2.154$, $p = 0.003$) but not for age $\times$ frequency ($F(12, 1645) = 1.240$, $p = 0.249$), age $\times$ tempo ($F(8, 1645) = 0.502$, $p = 0.855$), age $\times$ intensity ($F(2, 1645) = 0.473$, $p = 0.623$), frequency $\times$ intensity ($F(6, 1645) = 0.246$, $p = 0.961$), or tempo $\times$ intensity ($F(4, 1645) = 0.535$, $p = 0.710$). The brake response time results showed a statistically significant effect of age ($F(2, 1568) = 258.579$, $p = 0.00$) but not for frequency ($F(6, 1568) = 0.338$, $p = 0.917$), tempo ($F(4, 1568) = 0.424$, $p = 0.791$), intensity ($F(1, 1568) = 0.635$, $p = 0.426$), age $\times$ frequency ($F(12, 1568) = 0.749$, $p = 0.704$), age $\times$ tempo ($F(8, 1568) = 0.860$, $p = 0.550$), age $\times$ intensity ($F(2, 1568) = 0.091$, $p = 0.913$), frequency $\times$ tempo ($F(18, 1568) = 0.275$, $p = 0.999$), frequency $\times$ intensity ($F(6, 1568) = 0.546$, $p = 0.702$), or tempo $\times$ intensity ($F(4, 1568) = 0.546$, $p = 0.702$).

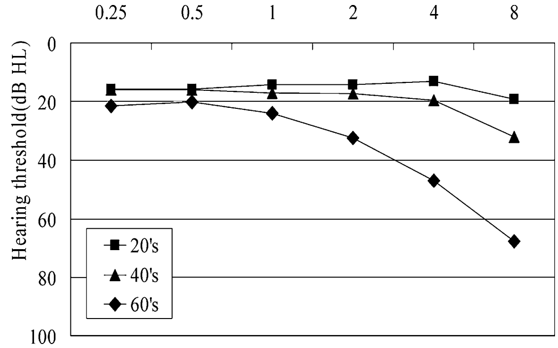

Fig. 4. Pure tone audiogram result of age groups at the Daegu Fatima Hospital.

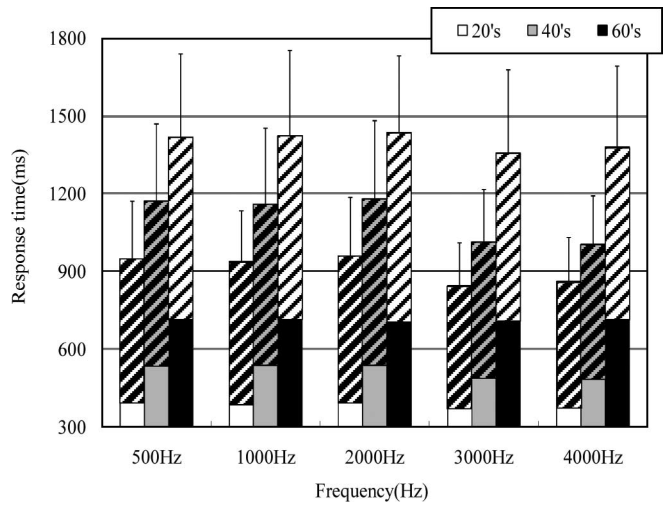

Fig. 5. Response time for various frequencies according to age group.

Fig. 5 shows the physical responses of the drivers by age according to various safety warning-sound frequencies. The upper part of the bar (oblique lines) represents the accelerator response time, whereas the lower part is the brake response time. It shows that response time increased from 0.5 to 2 kHz and slightly reduced from 3 to 4 kHz, drivers had the shortest accelerator response time at 3 kHz with significant difference for the range of frequencies. Thus, drivers including older driver responded fastest to the 3–4 kHz safety warning, a result that can be explained by the resonance of external ear to amplify around the 3–4 kHz from equal-loudness curves, which indicate that people perceive sound best at a frequency of 3–4 kHz [24], [25]. Due to age-related deficits such as cognitive decrement, physical response

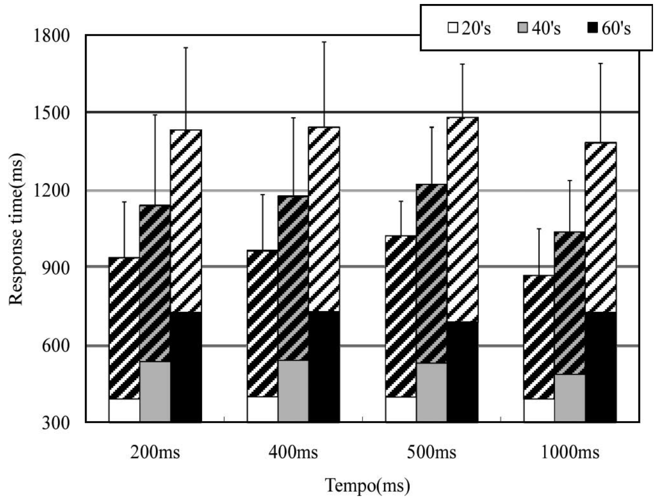

Fig. 6. Response time for various tempos according to age group.

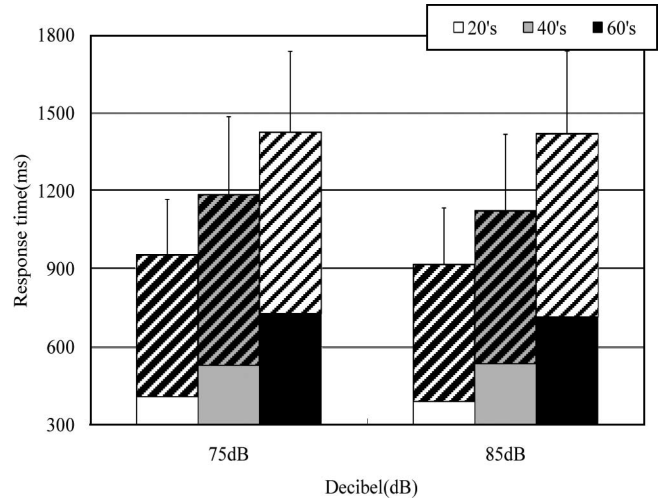

Fig. 7. Response time for different intensities according to age group.

decrement, and hearing loss, the average accelerator response time of older drivers was 160 ms longer than that of drivers in their twenties (minimum difference of 125 ms at 1.5 kHz, maximum of 184 ms at 4 kHz) and it was 100 ms longer than that of drivers in their forties (minimum difference of 66 ms at 0.5 kHz, maximum of 147 ms at 4 kHz). Older drivers' average brake response time was also longer than that of drivers in their twenties (318 ms; minimum difference of 304 ms at 0.75 kHz, maximum of 335 ms at 4 kHz) and 40s (187 ms; minimum 160 difference of ms at 2 kHz, maximum 228 ms at 4 kHz), respectively.

Fig. 6 shows the physical responses of drivers by age for different safety warning sound tempos. The upper part of the bar (oblique lines) represents the accelerator response time, and the lower part is the brake response time. The accelerator response times were faster for longer sound tempos, because longer sound tempos occurred for a long time with starting. But no significant difference was found in brake response time. The result of the tempo change test was similar to that of the frequency change test. The average accelerator response time of older drivers was 160 ms longer than that of drivers in their twenties (minimum difference of 150 ms for a tempo of 400 ms, maximum 180 ms for a tempo of 1000 ms) and 90 ms longer than that of drivers in their forties (minimum difference of 79 ms for a tempo of 300 ms, maximum 110 ms for a tempo of 1000 ms). The average brake response time of older drivers was 319 ms longer than that of drivers in their twenties (minimum difference of 290 ms for a tempo of 500 ms, maximum 334 ms for a tempo of 200 ms) and 185 ms longer than that of drivers in their forties (minimum difference of 157 ms for a tempo of 500 ms, maximum 238 ms for a tempo of 1000 ms).

Fig. 7 shows the physical response of drivers by age for different warning-sound intensities. The upper part of the bar (oblique lines) represents the accelerator response time while the lower part is the brake response time. Drivers in their twenties and forties had shorter accelerator response times as the warning sounds became louder, whereas older drivers showed no significant difference. In other words, older drivers are less sensitive to changes in warning sound intensity. The average accelerator response time of older drivers was 170 ms longer than that of drivers in their twenties (minimum difference of 163 ms for 75 dB, maximum 178 ms for 85 dB) and 86 ms longer than that of drivers in their forties (minimum difference of 55 ms for 75 dB, maximum 118 ms for 85 dB). The average brake response of older drivers was 316 ms longer than that of drivers in their twenties (minimum difference of 307 ms for 75 dB, maximum 324 ms for 85 dB) and 182 ms longer than that of drivers in their forties (minimum difference of 185 ms for 75 dB, maximum 178 ms for 85 dB).

B. *Emotional Characteristics*

The results of the tests of perceived danger showed a statistically significant effect of to age ($F(2, 1990) = 6.218$, $p = 0.02$), frequency ($F(6, 1990) = 26.503$, $p = 0.00$), tempo ($F(4, 1990) = 66.901$, $p = 0.00$), intensity ($F(1, 1990) = 369.794$, $p = 0.00$), age $\times$ frequency ($F(12, 1990) = 2.824$, $p = 0.001$), age $\times$ tempo ($F(8, 1990) = 3.782$, $p = 0.000$), frequency $\times$ tempo ($F(18, 1990) = 5.704$, $p = 0.000$), age $\times$ intensity ($F(2, 1990) = 3.036$, $p = 0.048$), frequency $\times$ intensity ($F(6, 1990) = 2.725$, $p = 0.012$), tempo $\times$ intensity ($F(4, 1990) = 2.603$, $p = 0.034$).

Fig. 8 shows the perceived danger level for various safety warning-sound frequencies. The drivers perceived the highest level of danger at a frequency of 3 kHz and the least at 2 kHz. In other words, a 3-kHz safety warning was perceived as indicating the highest level of danger because it sounded relatively louder than the sounds at other frequencies from equal-loudness curves [24], [25] and cognitive processing. The level of perceived danger in decreasing order corresponded to frequencies of 3.0, 0.75, 4.0, 2.0, and 1.5 kHz.

Fig. 9 shows the perceived level of danger for various safety warning-sound tempos. The drivers felt more danger as the tempo became shorter, and they experienced the greatest anxiety at a tempo of 200 ms. In other words, the sounds with shorter tempos were perceived as indicating more danger because they made the drivers feel more nervous. Moreover, the level of danger perceived by older drivers did not vary as much as that perceived by drivers in their twenties; among older drivers, less difference in elicited anxiety was observed between the highest (200 ms) and the lowest (500 ms) tempos. The warning sound tempo thus had less influence on older drivers.

Fig. 10 shows the perceived level of danger level for various warning sound intensities. It shows that drivers perceived more danger when the intensity was louder, and louder warning sounds were perceived as indicating more danger because they made the drivers feel more nervous.

The results of the preference tests showed a statistically significant effect of age ($F(2, 1990) = 11.941$, $p = 0.00$), frequency ($F(6, 1990) = 17.405$, $p = 0.00$), tempo ($F(4, 1990) = 3.156$, $p = 0.013$), intensity

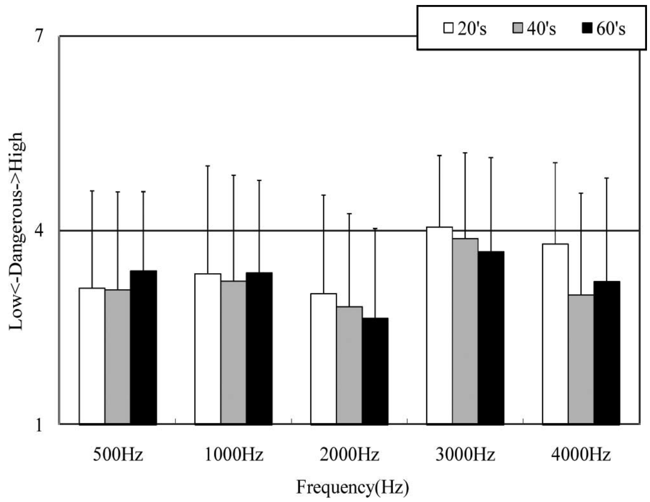

Fig. 8. Perceived level of danger for various frequencies according to age group.

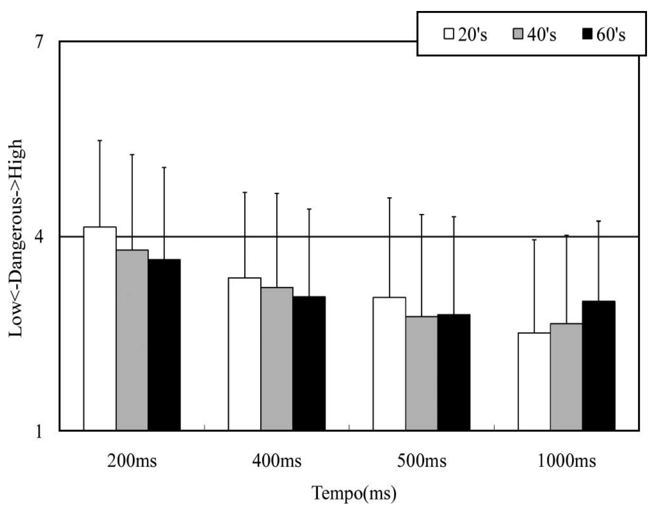

Fig. 9. Perceived level of danger for various tempos according to age group.

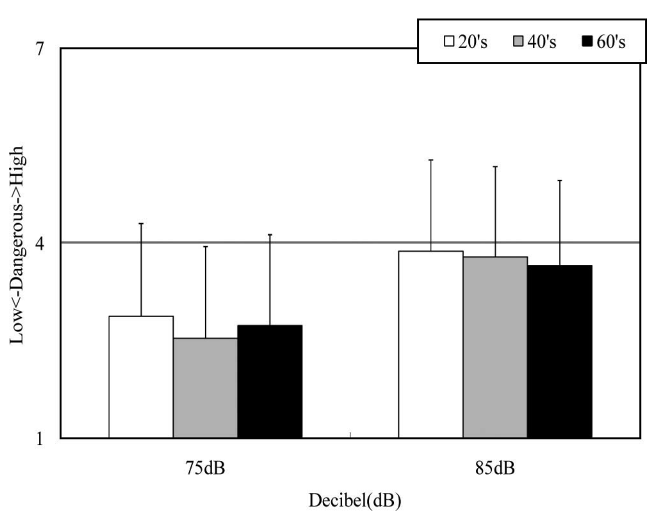

Fig. 10. Perceived level of danger for different intensities according to age group.

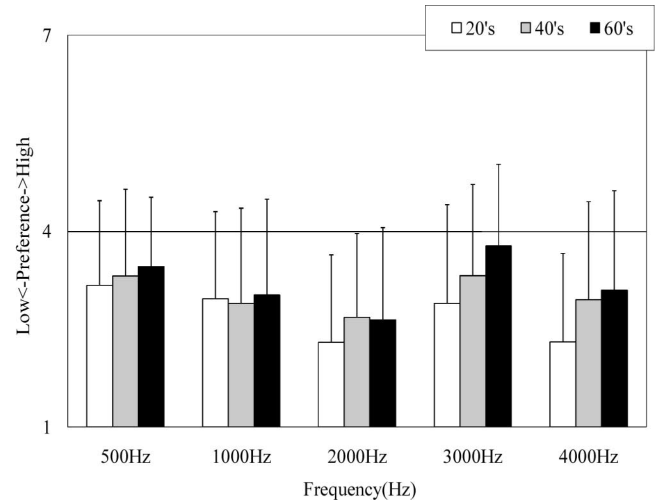

Fig. 11. Driver preference for various frequencies according to age group.

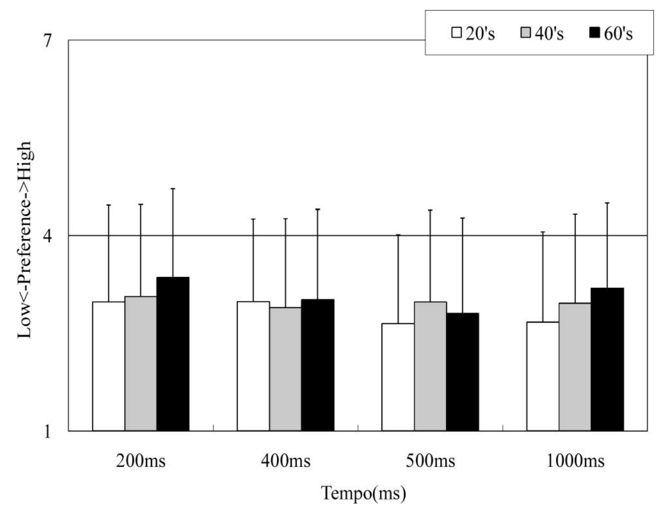

Fig. 12. Driver preference for various tempos according to age group.

($F(1, 1990) = 40.060$, $p = 0.00$), frequency × tempo ($F(18, 1990) = 2.082$, $p = 0.005$), and age × intensity ($F(2, 1990) = 3.809$, $p = 0.022$) but not for age × frequency ($F(12, 1990) = 1.288$, $p = 0.219$), age × tempo ($F(8, 1990) = 0.921$, $p = 0.498$), frequency × intensity ($F(6, 1990) = 1.131$, $p = 0.341$), or tempo × intensity ($F(4, 1990) = 1.199$, $p = 0.309$).

Fig. 11 shows the driver preference for various warning-sound frequencies. Drivers preferred the 3-kHz sound most and the 2-kHz sound least. Similar to the test of perceived danger, in decreasing order, drivers preferred the sounds at 3.0, 0.75, 4.0, 2.0, and 1.5 kHz.

Fig. 12 shows the driver preference for various warning-sound tempos. It shows that drivers perceived greater danger with a shorter tempo, and they most preferred the sound with the 200-ms tempo. However, compared to the test of perceived danger, the variation of the preference was smaller; the warning-sound tempo was found to have less influence on driver preference.

Fig. 13 indicates driver preference for different warning sound intensities. It shows that drivers preferred the louder sound; however, older drivers preferred the louder sound far more than did drivers in their twenties, who showed only a marginal difference in preference. The difference in preference was smaller than that found in the

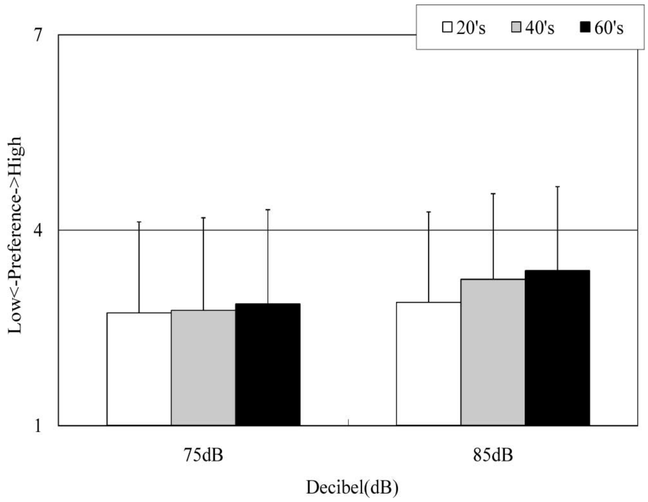

Fig. 13. Driver preference for various intensities according to age group.

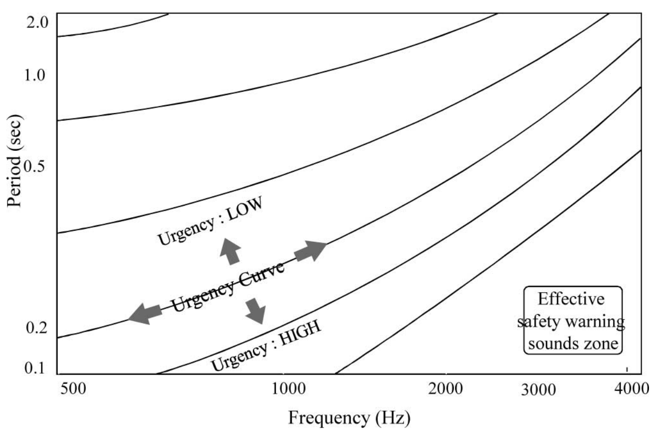

Fig. 14. Safety-warning sound guideline for vehicles with ADAS warning systems used by older drivers.

assessment of perceived danger; i.e., the intensity of warning sounds had less influence on preference.

C. Discussion

These experiments show that consideration of the frequency, tempo, and intensity is essential when designing safety-warning sounds. In particular, a 3–4 kHz sound proved to be the most effective in terms of physical response as well as emotional preference and perceived danger level. Moreover, sounds with a 200-ms tempo were found to be best in terms of the perception of danger and participant preference, according to the results of the emotional characteristic experiments while the accelerator response times were faster for longer sound tempos. As indicated in Fig. 14, the frequency of safety warning sounds should be around 3–4 kHz, and the tempo should be around 200 ms. Moreover, the frequency and tempo of other sounds used in cars should be 1 kHz and 500 ms, respectively, to avoid confusing drivers. Because many older drivers in particular are not able to distinguish safety warning sounds from other general warning sounds, respecting the suggested frequency and tempo is very important in the design of warning sounds.

Furthermore, differences were found in accelerator response time (160 ms) and brake response time (320 ms) between young drivers and older drivers due to age-related hearing loss and declining muscular strength. This must be considered when designing warning sounds and ADAS. Warning sounds designed for average drivers may lead to more frequent accidents with senior drivers due to longer response times, even when they recognize the warning sounds. Therefore, ADAS systems should trigger about 480 ms earlier.

IV. Summary and Conclusion

This paper has suggested an appropriate range of safety warning sounds based on an analysis of physical and emotional characteristics of drivers of various ages using a simulated driving situation. The response of older drivers to varying frequencies, tempos, and intensities was evaluated to establish guidelines for appropriate warning sounds. In addition, a qualitative analysis of driver response time as a function of age provided useful data for designing a vehicle safety system based on driver age. The results led to the following conclusions.

First, older drivers were significantly statistically different in the way they perceived warning sounds, depending especially on the frequency, but also on the tempo and intensity.

Second, older drivers showed differences in accelerator and brake response times compared to drivers in their twenties. More specifically, senior drivers responded to warning sounds about 160 and 320 ms later in releasing the accelerator and applying the brake, respectively, independent of the warning sound characteristics. These differences should be considered in the design of safety systems.

Finally, consideration of the physical and emotional characteristic of senior drivers is required when selecting safety-warning sounds. Safety warning sounds should have a frequency of 3–4 kHz and a tempo of 200 ms.

Follow-up studies of the physical and emotional preference to sounds with various attributes to warn of head-on collision or lane deviation are required. In addition, it is necessary to assessment of physical and emotional characteristics to auditory, visual, tactile warnings and the combination of two or more types of warnings. More research into physical and emotional characteristics to apply systemic safety system design such as ACC or LDWS is also required.

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