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Pedal Errors Among Younger and Older Individuals During Different Pedal Operating Conditions

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Objective: The objective of this study was to investigate the characteristics of pedal errors by younger and older drivers that relate to sudden unintended acceleration (SUA) accidents.

Background: SUA during an accident is a serious issue that causes numerous critical injuries and deaths every year. Previous studies have indicated that the major factor in these accidents is pedal error; however, the characteristics that relate to SUA accidents in older drivers remain unclear.

Method: Twenty younger drivers (YDs; 23.1 ± 0.22 years) and 20 older drivers (ODs; 68.9 ± 1.16 years) used either one or both feet to participate in six tasks that involved pressing accelerator or brake pedals in response to various visual stimuli.

Results: Both the reaction times (RTs) and the pedal error rates of the YD and OD groups significantly increased with the difficulty of the task. Other than the simple reaction condition, we found that the pedal error rates were significantly higher for the OD group than for the YD group; the OD group also demonstrated longer RTs. Moreover, the rates of accelerator error were consistently two or three times higher than the rates of brake error in both the YD and OD groups.

Conclusion: For the older population, the use of the left foot to operate the brake pedal and the right foot to operate the accelerator could decrease the accelerator error rate and may reduce the rate of SUA-related accidents that are caused by pedal error.

Keywords: pedal error, sudden unintended acceleration, aging effect, motor vehicle accident

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INTRODUCTION

Among nonintentional injuries in Japan, motor vehicle accidents are one of the most important causes of deaths, hospitalizations, medical treatments, and disabilities. Sudden unintended acceleration (SUA) during an accident is a serious issue that leads to numerous critical injuries and deaths every year. In 2008, more than 6,500 accidents involving SUA occurred in Japan, resulting in the death or injury of approximately 10,000 individuals (Ministry of Land, Infrastructure, Transport and Tourism, Japan [MLIT], 2009). Moreover, MLIT (2009) data also indicate that the incidence of SUA in accidents that result in injury or death increases sharply after age 60. Although it is possible that electrical or mechanical defects could be the cause of SUA events, previous studies (Schmidt & Young, 2010) have indicated that the major contributor to SUA in motor vehicle accidents is pedal error.

In the 1980s, the U.S. National Highway Traffic Safety Administration (NHTSA) first defined the concept of SUA, which had attracted considerable attention at that time. In particular, SUA is an unintended, unexpected, and high-powered acceleration from a stationary position or a very low initial speed that is accompanied by an apparent loss of braking effectiveness. To reduce the incidence of SUA, automakers began equipping vehicles with a shift-interlock system in the 1980s. This system prevented vehicles from moving into a forward or reverse gear after the engine was started unless the driver's foot was depressing the brake pedal. This device can effectively reduce the incidence of an SUA when a vehicle is first started. However, drivers may sometimes confuse the brake and accelerator pedals of a moving vehicle (Schmidt & Young, 2010), and the shift-interlock system cannot reduce the chances of an SUA at this time.

Several recent studies have focused on this topic and attempted to identify factors that could contribute to SUA by both younger and older individuals (Freund, Colgrove, Petrakos, & McLeod, 2008; Rogers & Wierwille, 1988; Schmidt, 1989; Schmidt & Young, 2010; Vernoy & Tomerlin, 1989; Young, Heckman, & Kim, 2011). Although these studies have provided important data regarding the frequency and type of pedal errors that occur during SUA-related accidents, the development of methods to reduce the rates of these types of accidents remains a key issue that must be addressed.

Aging-related deficits in cognitive ability are an important factor that affects the performance of older drivers (ODs). In fact, MLIT (2009) data have revealed that the incidence of all types of motor vehicle accidents is significantly higher among ODs than among younger or middle-aged drivers. The issue of the safety of ODs has received heightened attention in recent years, and authors of several studies (Bélanger, Gagnon, & Yamin, 2010; Makishita & Matsunaga, 2008; McGwin & Brown, 1999; Wu, Kodani, Yang, & Takahashi, 2011; Wu, Lu, Miyamoto, & Hayashi, 2009) have investigated impairments in the performance of ODs compared with younger drivers (YDs). These studies have indicated that ODs display deficits in a variety of respects; for instance, ODs evince longer reaction times (RTs) during an emergency situation (Wu et al., 2011) and a higher crash rate in multiple synchronized reaction tasks that were conducted in a driving simulator (Bélanger et al., 2010). As mentioned previously, the notion that age-related cognitive decline may lead to compromised driving performance has also been supported by previous research results involving older patients (Carr, Duchek, & Morris, 2000; Drachman & Swearer, 1993; Stein & Dubinsky, 2011). To the best of our knowledge, however, the characteristics of ODs with respect to SUA accidents (in particular, the incidence of pedal error in these accidents) remain unknown.

In this study, we designed a pedal-pressing experiment with different visual stimuli and foot movement sequences to investigate the characteristics of pedal error in YDs and ODs. Typically, pedal errors that result in an SUA-related accident occur during complex traffic situations; therefore, visual cues that would be found on the street, such as the color of a traffic light or the presence of a traffic jam, were used to induce the pedal errors. Other factors that might affect drivers' operation of the pedals were also addressed, such as pedal design and placement within the vehicle (e.g., situations in which the brake and accelerator are too close to one another) and variation between operating both pedals with either one foot (i.e., the right foot controls both the brake and accelerator pedals) or both feet (i.e., the left foot controls the brake during the course of driving an automatic transmission car). In this controlled study, we selected one type of pedal placement and used a series of simple visual stimuli (colored filled circles) to examine how the difficulty of the task and foot movement sequences affected the pedal operation.

METHOD

Subjects

Two groups of right-handed subjects consented to participate in this study. The subjects had all obtained their driver's licenses at least 3 years prior to the testing and were all vehicle owners. The group of YDs consisted of 20 male volunteers ranging in age from 22 to 25 years (mean age = 23.1 ± 0.22 years). The group of ODs also consisted of 20 volunteers (4 female) ranging in age from 60 to 80 years (mean age = 68.9 ± 1.16 years). The Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) screens for cognitive status and is designed to assess basic mental functioning, including an individual's ability to recall specific facts, write, calculate numbers, and draw. All of the members of the OD group scored a 29 or 30 on the MMSE (average score = 29.4 ± 0.11) and were free of cognitive limitations in their daily life. None of the OD subjects had any history of neurological or psychiatric disease, and no OD subjects were taking any medications that affected the central nervous system at the time of testing. The handedness of the examined subjects was confirmed with the Edinburgh Handedness Inventory (Oldfield, 1971), which is a measurement scale that is used to assess the dominance of a person's right or left hand in everyday activities. Finally, all subjects reported

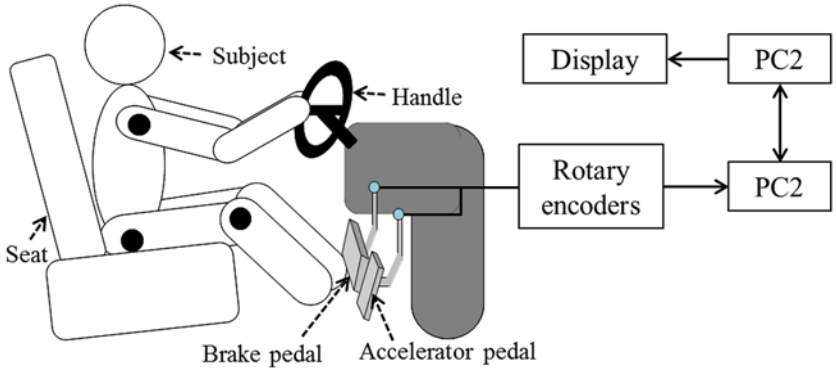

Figure 1. The experimental apparatus and the position of the subjects. PC = personal computer.

normal or corrected-to-normal vision and were unaware of the purpose of the study.

Apparatus and Stimuli

A dedicated experimental system (Figure 1) that consisted of a 40-in. visual screen, a pedal mechanism, and two computers was used for this study. The visual stimuli included a series of filled, colored circles (Conditions 1 through 4: green and red; Conditions 5 and 6: green, red, blue, and yellow) subtending 1.5 visual degrees that were presented against a black background at the center of the screen. A fixation cross (a white cross with a viewing angle of 1.5°) was presented at the center of the screen when no visual stimuli were present. The pedal mechanism included an accelerator pedal (85 mm high and 40 mm wide) and a brake pedal (55 mm high and 90 mm wide) that mimicked a right-hand-drive car. The distance between the two pedals was 70 mm, and the difference in depth between the pedals was 0 mm (i.e., the accelerator and brake pedals were in the same plane). Two rotary encoders were used to detect the angles of the accelerator and brake pedals, and two computers worked synchronously to control the experimental system and record the reaction data. The handle did not turn and was not connected to anything. Finally, to minimize any environmental distractions, all of the experiments were conducted in a darkened room.

Procedure and Task Design

The basic task was to press the accelerator or the brake pedal as quickly as possible in response to the appropriate visual stimuli. We asked the subjects to place both hands on the steering wheel in front of the screen and keep their eyes focused on the fixation cross. The subjects were also asked to place their right foot lightly on the accelerator pedal (to mimic driving at a very low speed on the street) and to keep their left foot on the rest stand as the initial position for the one-foot condition. In the conditions involving two feet, the subjects were asked to lightly place their left foot on the brake pedal. To ensure that all the subjects could perform each task accurately, the subjects were allowed to practice the foot movements involved in each experimental condition 10 times before starting.

Condition 1 was a simple reaction task (SRT) that involved two types of visual stimuli, namely, green and red circles. The visual stimuli were presented for 200 ms in the center of the screen at randomly determined intervals of 4,000 or 6,000 ms. The subjects were instructed to press the accelerator pedal when either the green or the red visual stimulus was presented (Figure 2a). Condition 2 was a green selection task (GST) that was similar to the SRT except that the subjects were asked to ignore the red visual stimulus and press the accelerator pedal only when presented with the green visual stimulus (Figure 2b). Condition 3 was a green and red correspondence selection task involving the right foot (CSTr). The visual stimuli and timing were the same as in the SRT, but the subjects were asked to use their right foot to press the accelerator pedal when the green visual stimulus

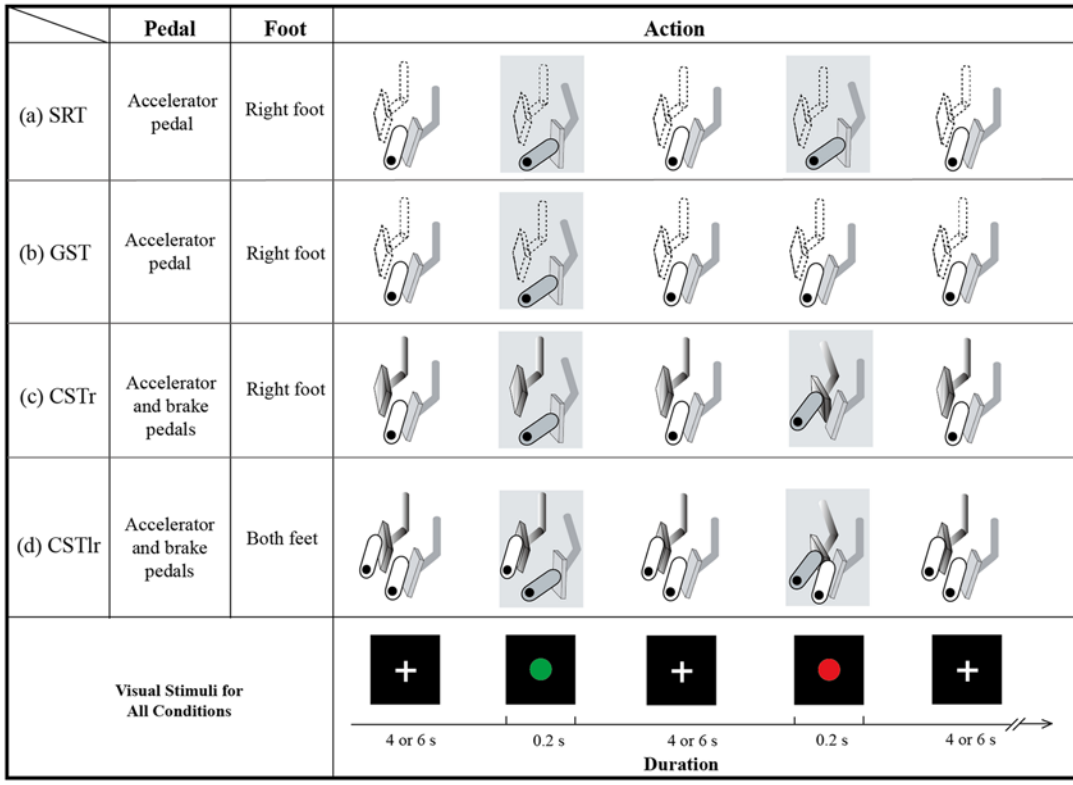

Figure 2. The trial paradigms for the (a) SRT, (b) GST, (c) CSTr, and (d) CSTlr conditions. The white foot indicates the initial position, and the gray foot indicates the required pedal action. In each condition, the subjects were asked to respond to the visual stimuli by pressing the corresponding pedal as quickly as possible. SRT = simple reaction task; GST = green selection task; CSTr = green and red correspondence selection task involving the right foot; CSTlr = green and red correspondence selection task involving both the left and right feet.

was presented and to press the brake pedal when the red visual stimulus was presented (Figure 2c). Condition 4 was a green and red correspondence selection task involving both the left and right feet (CSTlr). The procedure was the same as that of the CSTr, but the subjects were asked to press the accelerator pedal with their right foot and the brake pedal with their left foot in response to the green and red visual stimuli, respectively (Figure 2d). For each condition, the green and red visual stimuli were each presented 72 times for a total of 144 trials.

Condition 5 was a four-color correspondence selection task involving the right foot (FSTr). The FSTr involved four types of visual stimuli that consisted of green, red, yellow, and blue circles. The subjects were asked to ignore both the yellow and blue visual stimuli and to use their right foot to press either the accelerator pedal in response to the green visual stimulus or the brake pedal in response to the red visual stimulus. Condition 6 was a four-color correspondence selection task involving both the left and right feet (FSTlr). The procedure for this task was the same as the procedure in the FSTr except that in the FSTlr, the subjects were asked to respond to green and red visual stimuli by pressing the accelerator pedal with their right foot and the brake pedal with their left foot, respectively (Figure 3b). Each of the four visual stimuli was presented 36 times during each condition, and a total of 144 trials were performed in each condition.

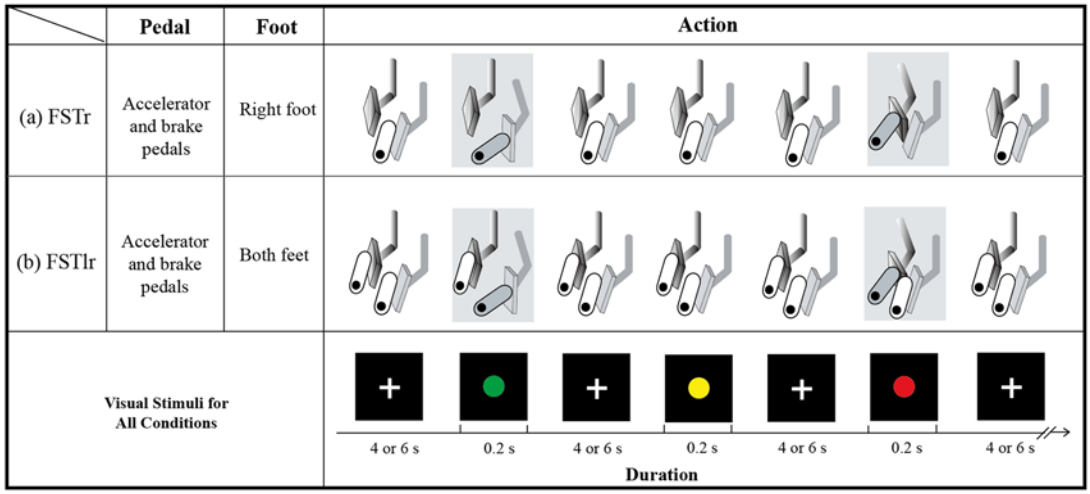

Figure 3. The trial paradigm for the (a) FSTr and (b) FSTlr conditions. The white foot indicates the initial position, and the gray foot indicates the required pedal action. In each condition, the subjects were asked to react to the visual stimuli by pressing the corresponding pedal as quickly as possible. FSTr = four-color correspondence selection task involving the right foot; FSTlr = four-color correspondence selection task involving both the left and right feet.

Data Processing and Analysis

The mean pedal error rate was computed for each subject in each condition. Pedal errors included the following three situations: pressing the pedal in response to the fixation cross, pressing the pedal in response to an irrelevant visual stimulus, and failing to react when a green or red visual stimulus was presented (with the exception of a red stimulus in the GST). The accelerator and brake RTs were calculated from the time of the onset of the visual stimulus to the time when the accelerator or brake pedal was pressed. Differences in pedal error rates and RTs between the two subject groups were analyzed with repeated-measures analyses of variance (ANOVAs). The level of significance was fixed at $p < .05$. Bonferroni tests ($\alpha = .05$) were performed to detect any differences between conditions or subject groups.

RESULTS

RT

The mean accelerator and brake RTs of the YD and OD groups in all of the tested conditions are presented in Figure 4. We found significant differences in the mean RTs across all of the conditions, $F(9, 342) = 324.04$, $p < .001$. In particular, in the YD group, the results revealed that the accelerator RTs significantly differed among the various one-foot conditions, with an ordering of SRT < GST < CSTr < FSTr for these RTs ($p < .05$ in all cases). However, we did not observe any significant differences in accelerator RTs between the conditions involving one or two feet (i.e., for CSTr vs. CSTlr and FSTr vs. FSTlr; $p > .05$ in both comparisons). Moreover, we determined that the brake RTs in the CSTr were significantly shorter than the brake RTs in the FSTr ($p < .001$); a similar difference was observed between the CSTlr and FSTlr conditions ($p < .001$). These aforementioned RT relationships for the YD group were also found for the OD group (Figure 3b). Finally, we found that the accelerator RTs of the YD group were significantly shorter than the accelerator RTs of the OD group in the GST, CSTr, FSTr, CSTlr, and FSTlr conditions ($p < .05$ in all cases). However, there were no significant group differences in brake RTs between the YD and OD groups in any of the examined conditions ($p > .05$).

Pedal Error Rate

To investigate differences in pedal errors across the different conditions, we calculated

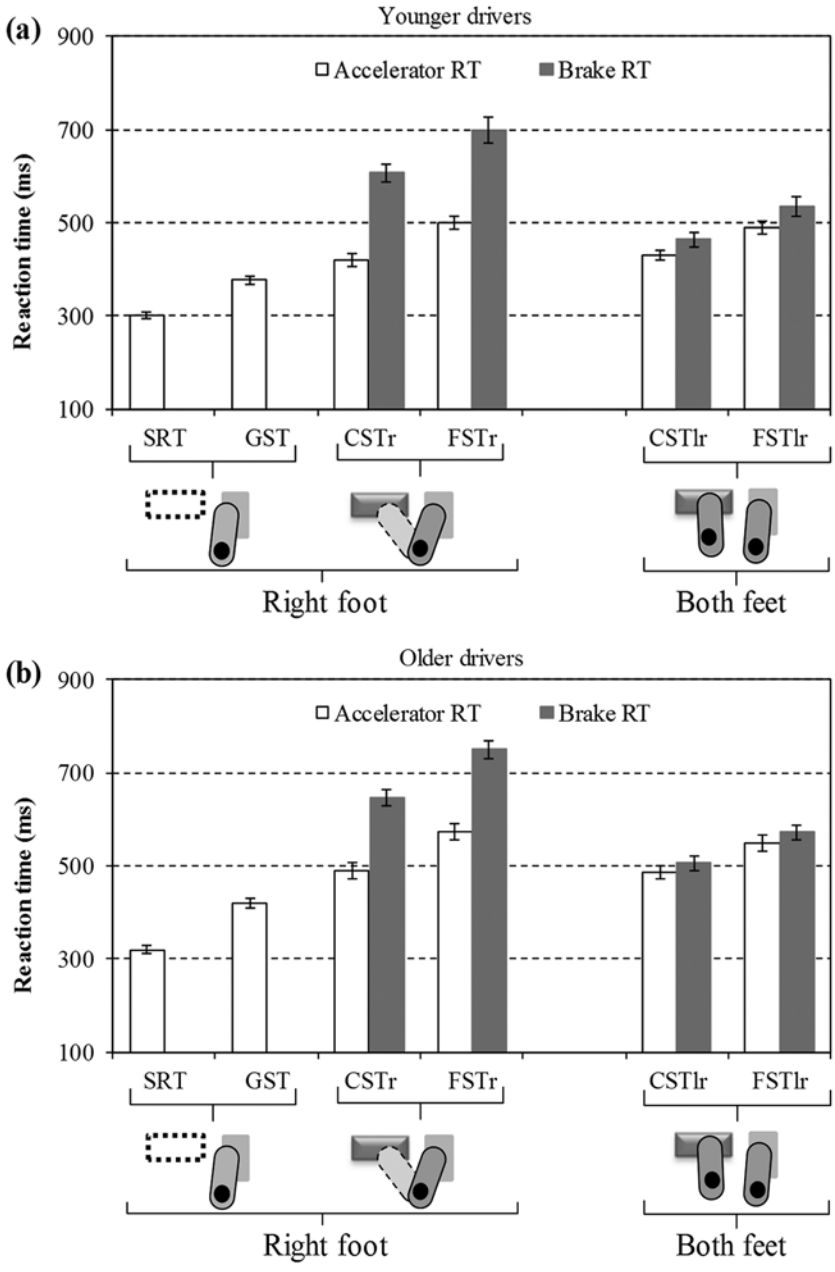

Figure 4. The mean reaction times (RTs) of the (a) younger driver and (b) older driver groups for each condition. For each condition, the white bars represent the mean accelerator RTs, and the gray bars represent the mean brake RTs. The error bars represent the means ± SEM. SRT = simple reaction task; GST = green selection task; CSTr = green and red correspondence selection task involving the right foot; CSTlr = green and red correspondence selection task involving both the left and right feet; FSTr = four-color correspondence selection task involving the right foot; FSTlr = four-color correspondence selection task involving both the left and right feet.

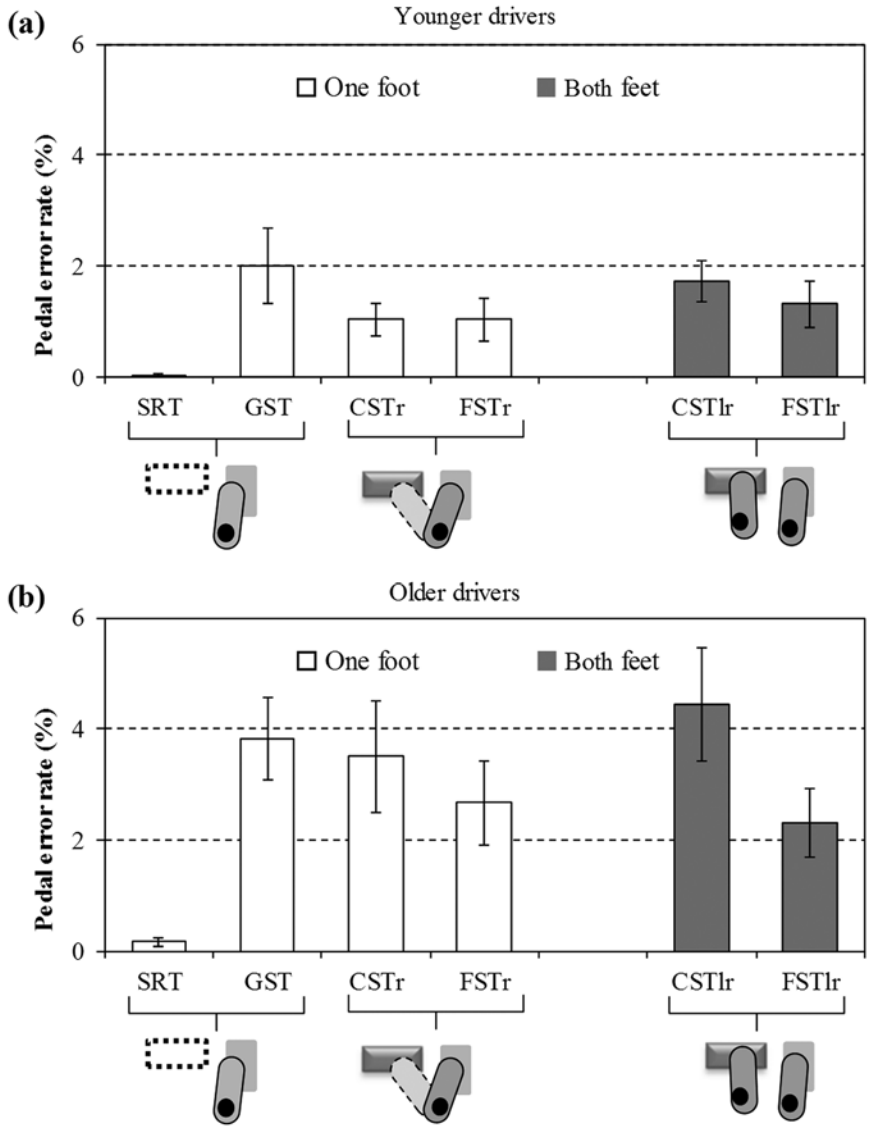

Figure 5. The mean pedal error rates of the (a) younger driver and (b) older driver groups for each examined condition. For each condition, the white bars represent mean accelerator error rates, and the gray bars represent mean brake error rates. The error bars represent the means ± SEM.

the mean pedal error rate for each condition in the YD and OD groups (Figure 5a and 5b, respectively). We found significant differences in the mean pedal error rates across all of the examined conditions, $F(5, 190) = 11.88$, $p < .001$. For the YD group, we did not find any significant differences in pedal error rate across the various conditions that were examined ($p > .05$ in each case). By contrast, the OD group exhibited a significantly lower pedal error rate under the SRT condition compared with the other five conditions ($p < .01$ for all of the comparisons). Moreover, we found that the pedal error rates of the YD group were significantly lower than the pedal error rates of the OD group in the CSTr, FSTr, and CSTlr conditions ($p < .05$ in each

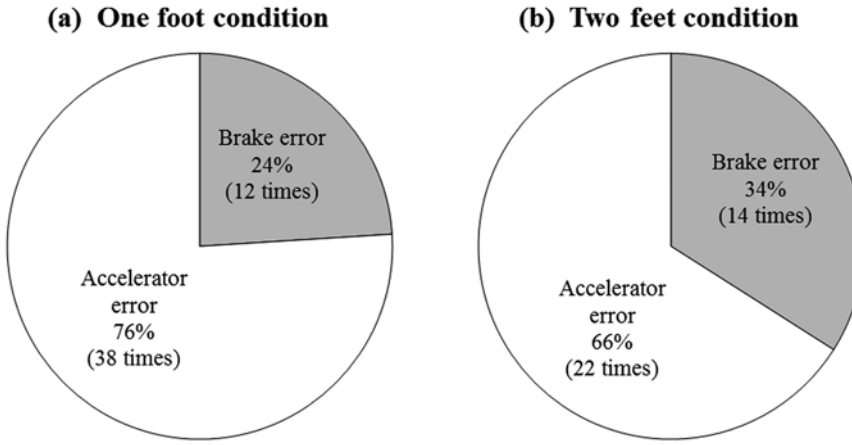

Figure 6. The accelerator and brake pedal errors from the use of (a) one foot and (b) two feet by the young driver group.

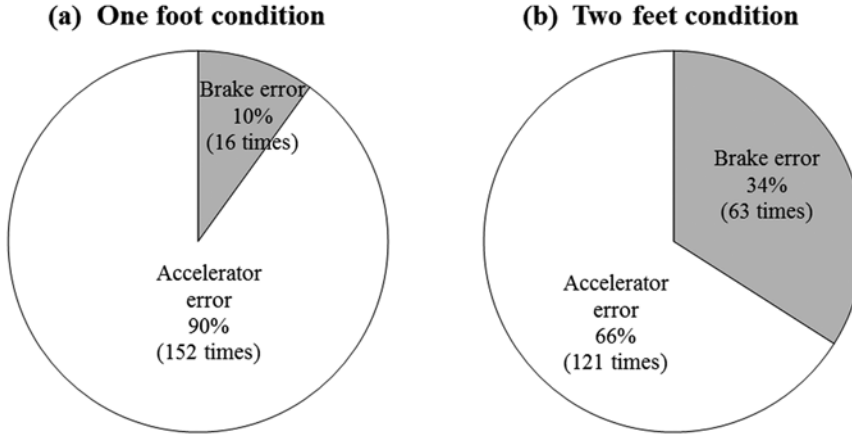

Figure 7. The accelerator and brake pedal errors from the use of (a) one foot and (b) two feet by the older driver group.

case) but not in any of the other three conditions ($p > .05$ for these three conditions).

We also analyzed the pedal error patterns of the YD and OD groups for all of the conditions that involved one or two feet. The results for the YD and OD groups are depicted in Figures 6 and 7, respectively; in particular, the white portions of each graph illustrate the percentages of accelerator error (i.e., pressing the accelerator pedal if no visual stimulus or an inappropriate visual stimulus was presented), and the gray portions of each graph represent the percentages of brake error. These results indicate that the accelerator error rate was two or three times higher than the brake error rate in all of the tested conditions for both the YD and OD groups. Moreover, the ODs committed more accelerator errors than the YDs in the one-foot conditions; however, this difference between groups was not observed in the conditions involving two feet.

DISCUSSION

This study contrasted the performances of YDs and ODs in six pedal-pressing tasks that involved varying visual stimuli and the use of either one foot or both feet. The results suggest that the pedal error rates of the OD group were significantly higher than the pedal error rates of the YD group; in addition, the OD group

exhibited longer RTs. Our primary result is that the pedal error pattern of the OD group differed from the pedal error pattern of the YD group. As shown in Figure 7, the experimental results indicated that the older drivers committed significantly fewer accelerator errors if they used both feet to operate the brake and accelerator pedals than if they used only one foot for both pedals.

The Effects of Aging on Pedal Operation

Many variables have been thought to reflect the speed of processing, and most are strongly related to age (Mouloua et al., 2004). For example, previous investigations have demonstrated that ODs perform significantly worse with respect to detecting peripheral road signs on driving courses (Chaparro, Wood, & Carberry, 2005). Our recent studies have also indicated that compared with YDs, ODs require longer times to brake during emergency situations (Wu et al., 2011) and have smaller kinetic visual fields (Wu et al., 2009). Moreover, the published work of Karlene Ball and colleagues (Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Owsley et al., 1998) has indicated that reductions in the useful field of view (UFOV) are significantly associated with increased rates of vehicular crashes in ODs. In fact, the UFOV assessment is commonly used not only for traffic safety research (Ball et al., 2006; Edwards et al., 2009) but also in the real world. In this study, we also found that compared with YDs, ODs evinced significantly longer RTs and higher pedal error rates in all of the examined conditions except the SRT (Figures 4 and 5).

In the SRT, the subjects were asked to simply press the accelerator pedal if they observed any visual stimulus (Figure 2a). Thus, the subjects did not need to exert any effort during the movement planning period. However, the other five tested conditions required the more complex cognitive processes of discriminating the color of the visual stimuli and selecting a plan of action to press a pedal. Therefore, our data suggest that declines in the cognitive processes of ODs with respect to movement planning during pedal operation may lead to longer RTs and higher pedal error rates for the OD group than for the YD group. This reasoning is supported by previously published studies, which have indicated that several cognitive functions decline with age (Bugaiska et al., 2007; Mouloua et al., 2004).

Pedal Error Patterns of YDs and ODs

In Japan, drivers who are operating a car with an automatic transmission learn to operate both the accelerator and brake pedals with their right foot; most drivers press the pedals in accordance with this training. However, the use of the left foot for the brake pedal and the right foot for the accelerator pedal also occurs in Japan. As described in the Results section, we did not observe any difference in the overall RTs or pedal error rates between the one-foot and two-feet conditions. We then analyzed the pedal error patterns of drivers who were using either one foot or both feet (Figures 6 and 7). Compared with the YD group, the OD group demonstrated more accelerator errors in the one-foot conditions but not in the two-feet conditions. This result suggests that the use of the left foot to operate the brake pedal and the right foot to operate the accelerator may decrease the accelerator error rates of ODs. Thus, the operation of vehicle pedals with both feet may reduce the rate of SUA-related accidents that are caused by pedal errors of ODs.

In summary, the key risk factor of pedal errors for ODs is functional impairment, which is often the product of age-related declines. This factor constitutes a different risk pattern from that found in YDs, where risk-taking behavior is the key contributor. It is difficult to counter functional impairments directly through driver education, but it is possible to educate ODs about how their impairments may affect their pedal operation and to facilitate the acquisition of compensatory strategies. For example, using both feet to operate the brake and accelerator pedals could decrease the accelerator error rate.

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KEY POINTS

- The main factor that affected pedal errors during driving-related behaviors was the difficulty of the task.
- Age-related impairments in cognitive functions in older drivers are a potential cause for the high incidence of sudden unintended acceleration (SUA) accidents.
- The operation of the pedals with both feet may reduce the rate of SUA-related accidents that are caused by pedal error in older drivers.

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