KOCHI UNIVERSITY OF TECHNOLOGY

Social Design Engineering Series *SDES-2017-16*

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29th August, 2017

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Abstract

In the aging information society, replacing human passengers' protective effects on vehicle drivers with those of social robots is essential. However, effects of social robots' presence on drivers have not yet been fully explored. Thus, using a driving simulator and a conversation robot, this experimental study aimed to answer two research questions: (i) whether social robots' anthropomorphic qualities per se—not practical information the robot provides drivers—have protective effects by promoting cautious driving and alleviating crash risks and (ii) in what psychological processes such effects emerge. Participants were collected from young, middle-aged, and elderly cohorts (n = 37, 36, and 36, respectively). They were allocated to either the treatment group (simulated driving in a conversation robot's presence) or the control group (simulated driving alone), and their driving performance was measured. Emotions (peace of mind, loneliness, and concentration) were also measured in a post-driving questionnaire survey using our original, psychometrically sound scales. Although the older cohort did not demonstrate protective effects, perhaps due to motion sickness, young and middle cohorts drove cautiously, with the robot enhancing either peace of mind or concentration. Protective effects were partly ascribed to the robot's role of expressing sympathy, especially when drivers encountered not-their-fault minor incidents and became stressed. This finding suggests a new driving-safety approach, in which the central point is passengers receiving drivers' emotions, rather than giving them information or warnings, regardless of whether passengers are humans or social robots.

Key words: Passenger effects on drivers, Social Robots, Weak AI stance.

1. Introduction

Mobility is a basic human need, and securing the need of those who hope to drive, while also securing their need for safety, is essential. However, these needs are sometimes hardly compatible, especially for elderly people as drivers who have higher crash rates per vehicle-mile of travel (Massie, Campbell, & Williams, 1995; McGwin & Brown, 1999; Retchin & Anapolle, 1993) due to such factors as decline in their driving abilities. Some researchers in the field of traffic accidents believe that encouraging passengers to accompany drivers is one of the most promising measures to make these two needs compatible. These claims are based on empirical evidence that passenger presence alleviates crash risks under certain conditions (Hing et al., 2003; Lee & Abdel-Aty, 2008; Engstrom et al., 2008; Rueda-Domingo et al., 2004; Nakagawa & Park, 2013, 2014), although it has potentially negative effects under other conditions, for instance, annoyance, pique, flattery, vanity, and overdependence (e.g., Nakagawa & Park, 2014).

Human passengers' protective effects can be partly ascribed to supporting drivers in detecting critical situations (e.g., Vollrath, Meilinger, & Krüger 2002; Hing et al., 2003). In this sense, effects of passenger presence resemble those of "driving assistance systems" (e.g., Bengler et al., 2014) and smart vehicles (e.g., Rhiu et al., 2015). However, other protective effects seem to be ascribed to passengers' humaneness, which driving assistance systems do not seem to create, such as parent drivers' willingness to defend their child passengers and the active role of women passengers' attempts to modify male drivers' style to safer practices (Rueda-Domingo et al., 2004). More recently, after a questionnaire survey of drivers and factor analysis of data, Nakagawa and Park (2014) identified psychological factors of human passengers, including relief and responsibility, suggesting that some psychological consequences of human passengers are ascribed to passengers' presence itself, rather than the information they transfer to drivers.

To benefit from these humane protective effects, however, encouraging drivers always to drive with human passengers is absolutely impractical. For this reason, social robots with "the weak AI stance" (Duffy, 2003) are expected to contribute greatly to drivers' safety. Adopting this stance means *believing* that social robots (i.e., robots empowered to behave in a manner conducive to its goals and those of its community) are rational entities possessing intelligence and emotions, regardless of whether they are actually so intelligent. The promise of such social robots to encourage safe driving seems to be supported by psychological findings that even social cues (e.g., an image of a pair of eyes) change people's actual behaviors in both experimental and real settings (e.g., Bateson, Nettle, & Roberts, 2006). Social robots with higher degrees of anthropomorphic qualities may well do better than such cues.

In spite of social robots' promise, few earlier studies have investigated (i) whether social robots' anthropomorphic qualities per se, not the practicality of the information it gives to drivers, have protective effects on drivers by alleviating crash risks or promoting cautious driving, let alone (ii) in what psychological processes such effects emerge. Thus, the present experimental study aimed to answer these two research questions, using a driving simulator and a conversation robot whose talk is practically irrelevant, but possibly relevant emotionally. Question (ii) is answered by identifying psychological variables that mediate the association between the robot's presence and safe driving. Identification of such variables contributes not only to designing social robots to maximize their positive anthropomorphic effects, but also to understanding how human passengers can maximize protective effects on drivers. Thus, the present study is relevant to scholars in the field of safe driving, irrespective of whether they are interested in social robots or not.

Some earlier studies investigated drivers' psychological attitudes towards social robots or anthropomorphic entities, for instance, trust of autonomous vehicles (Wayts, Heafner & Epley, 2014), sense of mutual social exchange, and co-presence of a robot (Williams, Peters, & Breazeal, 2013; Williams, Flores, & Peters, 2014; Karatas et al., 2015). However, to the authors' knowledge, how these emotions contribute to safer driving is not yet clear. The description of such a process should include more general constructs as predictors of safe driving than constructs like trust of robots. They are more general in the sense that they can describe psychological states not only of drivers with robots, but also of those driving alone or with human passengers.

2. Conceptual Framework and Hypotheses

Figure 1 depicts the present study's conceptual framework. The hypotheses inherent in this framework are as follows. The causal relationship described in **H1** is expected to be partly explained in terms of two causal (chained) relationships described in **H2** and **H3**. The present study aims to test these three hypotheses.

H1: The treatment (i.e., driving in the presence of an anthropomorphic robot giving practically irrelevant, but possibly emotionally relevant comments) affects driving outcomes so that [A] the number of crashes decreases and [B] the cautiousness, as measured by time of completing a driving task, increases.

H2: The treatment affects drivers' emotions so that [A] peace of mind increases and [B] loneliness decreases.

H3: Drivers' emotions affect their driving outcomes so that [A] peace of mind and [C] concentration negatively affect [A] the number of crashes and positively affect [B] cautiousness, while [B] loneliness has opposite effects.

Several things should be noted. First, three emotions (i.e., [A] peace of mind, [B] loneliness, and [C] concentration) were selected so that the following criteria are satisfied: (i) They describe psychological states of drivers regardless of whether they drive alone, in the presence of human passengers, or in the presence of robot passengers. (ii) They could be affected either positively or negatively by social robots' presence. (iii) They could affect either positively or negatively driving outcomes.

Second, the expectation that the three emotions (i.e., [A] peace of mind, [B] loneliness, and [C] concentration) satisfy criterion (ii) is based on Williams, Flores, and Peters (2014), who showed that a robot's presence reduces mental stress (associated with [A] peace of mind), enhances adherence to safety (possibly associated with [C] concentration), and enhances co-presence (associated with [B] loneliness).

Third, the expectation that the three emotions satisfy criterion (iii) is based on the literature on human passenger presence. Young passengers' negative effects on young drivers' safety are partly explained in terms of distraction (e.g., Simons-Morton, Lerner & Singer, 2005), suggesting that [C] concentration (i.e., the opposite of distraction) satisfies criterion (ii) at least in the young cohort. Lee and Abdel-Aty (2008) suggest that human passengers help relieve drivers' impatience during traffic congestion and at other times. This interpretation seems consistent with our expectation of [C] concentration. (Note that if there is no patience, there is no concentration.) Finally, considering human passengers' role in enhancing drivers' responsibility to protect passengers' lives (Vollrath, Meilinger, & Kruger, 2002; Rueda-Domingo et al., 2004), it is suggested that drivers' loneliness ([B]) might negatively influence drivers' safety by lowering accidents' perceived cost.

Fourth, with the literature in mind, in **H2**, it should be noted that the association between treatment and [C] concentration is complex. Thus, this association's description was carefully omitted from this hypothesis. While it is expected that the sense of being watched over by an anthropomorphic entity promotes concentration because it accords with the social norm, it is also expected that such a robot and its comments can distract drivers. In the present study's statistical analysis, it is expected that a condition will be identified under which the positive association dominates the other.

3. Materials and Methods

3.1 Driving Simulator

The Honda Safety Navi is PC software for simulated driving with an automatic transmission vehicle. This simulator software can be operated by input devices including a steering wheel, the accelerator, and the brake pedals. The PC is connected to three monitors mimicking the windscreen and the left and right windows. In the present study, the PC installed with this software was connected with a conversation robot named Phyno. Measuring 260 mm × 210 mm × 340 mm and weighing 3 kg, Phyno is placed on a control box containing a computer. Phyno does not move, but has degrees of freedom (DOF) totaling five: 3 DOFs in its head and 1 DOF in its arms and torso, respectively. This conversation robot was integrated into Safety Navi. The robot can automatically choose predesigned words and speak them, depending on drivers' behaviors in the simulated driving course. An overview of the system is shown in Figure

1.

3.2 Event Design

To avoid motion sickness, a straightforward driving course was designed with a length of 15.6 km. The course consisted of two-lane roads (one lane each way), with a speed limit of 40km/h and one lane roads with a speed limit of 30 km/h. The simulator was adjusted so that once a driver accelerated the vehicle and the speed mounted to the limit, the speed is kept constant unless the driver intentionally steps on the brake pedal. This was done to exclude participants who unintentionally avoided crash risks only because the driver failed to press the acceleration pedal consistently to maintain constant vehicle speed.

The driving course was constructed by connecting the same straight road configuration with the length of 3.9 km four times (3.9 km/lap * 4 laps = 15.6 km). However, in each of the laps, events (e.g., movement of surrounding vehicles and pedestrians) were designed differently to secure event unpredictability. The list of 48 events in the four laps is summarized in Table 1.

3.3 Participants

Participants with driving licenses were recruited from three different cohorts: young (undergraduate or graduate students), middle (aged from 35 to 55), and old (aged 65 or over). Participants in the young cohort were recruited by the authors in Kyoto Sangyo University, while participants in the other two cohorts were recruited by temporary-employment agencies. Numbers of recruited participants were 38, 39, and 49, respectively.

In each of the three cohorts, research subjects were allocated either to the treatment or the control group. Those in the treatment group were accompanied by a conversation robot, which praised or encouraged the driver soon after events listed in Table 1. Regarding the 19 events with an asterisk in Table 1, the robot chose its statements according to whether crash risks were successfully avoided or not. For example, soon after event No. 18, the robot said, "Always think something might be there behind parked cars!" to those who failed. It said, "It was nice of you to recognize the bike!" to those who succeeded. In event No. 16, the robot said sympathetically, "That motor bike was crazy!" when drivers almost crashed, but successfully avoided doing so. The robot also warned, "Pay attention to motor bikes!" when drivers failed to do so. Regarding 20 events in which obeying traffic regulations is required, the robot praised drivers if they indeed obeyed, while otherwise, it alerted drivers. Note that in events above, whether the driver was successful or not was automatically identified. Finally, in addition to those occasions mentioned above, the robot intervened with the driver seven times during the normal period, in order to strengthen its presence with trivial statements like "This is a narrow road, isn't it?" and "No cars around here!" Note that this conversation robot provided drivers with feedback only to impress drivers that it was watching over their behaviors.

In predesigning the robot's phrases and sentences, special attention was paid so that the robot would never provide prospective information to participants, such as warnings and estimations of other vehicles' movement. The robot made only retrospective statements about participants' behaviors or those of other actors in past events. These comments must have seemed quite obvious and trivial to participants, but the objective was to make them feel as if the robot was always watching over their driving behaviors. The extent to which our attempt to give only practically irrelevant information was successful will be discussed in section 5.

3.4 Testing Procedure

At Kyoto Sangyo University, the experiment was conducted in a laboratory with an area of approximately 15 m^2. Upon arrival at the laboratory, a staff member briefed each participant on the experiment's objective and requirements. Then participants read and signed an informed consent document. Participants were given some basic information about the simulator's use, warned about simulator (motion) sickness, and informed that they could stop the test at any time. Drivers then performed a 5-min training phase to familiarize themselves with the vehicle and its control instruments. Next, the staff left the laboratory, and the participants proceeded to the experiment's main part alone.

For the treatment group, participants experienced a short conversation with the robot before the training phase, so they became accustomed to the robot's voice. The robot asked if the participants had confidence in driving in general. Regardless of the participants' answer, the robot provided a typical reply via manual operation by the staff.

3.5 Data Collection

Although the simulator recorded a great number of parameters to characterize participants' driving behavior, the present study utilized just two driving outcomes: the total number of crashes and the total time to drive the entire course. Regarding crashes, the range of numbers is less than or equal to 19, unless the driver intentionally causes crashes. To identify events that can cause crashes, see Table 1.

After the driving task was completed, participants were requested to complete a questionnaire containing items regarding (i) age, (ii) gender, (iii) type of driving license (limited to only automatic transmission/ full license), (iv) frequency of driving, (v) years or months since driving license was obtained, and (vi) emotions during driving (i.e., [A] peace of mind, [B] loneliness, and [C] concentration). Finally, for participants in the treatment group, we included (vii) an open-ended question on the experience of driving in the robot's presence.

Regarding (vi, emotions), the authors created and implemented 16 items. Participants were asked to rate on a five-point scale how each item described them, from 1 = "Strongly disagree" to 5 = "Strongly agree."

3.6 Analysis

Analysis was conducted in three phases. First, factor analysis was applied to the answers of (vi) emotions felt, and scales to measure the three psychological constructs were developed. In this step, participants in control and treatment groups were not distinguished. Second, hypotheses were tested. Specifically, **H1** was tested by comparing driving outcomes' mean values between control and treatment groups. **H2** was tested by comparing psychological scale scores' mean values. **H3** was tested by multivariate linear regression analysis in which driving outcomes were explained according to the three psychological scale scores. Third, treatment group participants' answers to the open-ended question about driving in the robot's presence were analyzed. Specifically, answers were coded and each code's frequency in each cohort was determined. These results were used to support statistical analysis results.

4. Results

The sample's characteristics are summarized in Table 2. Sizes of the young, middle, and old samples were 38, 39, and 49, respectively. Data of one, two, and 12 participants, respective to age group, were not used because data were lost due to the authors' mistake or because participants suspended the experiment due to motion sickness.

4.1 Development of Psychological Scales

Regarding factor analysis, after deletion of items contributing to more than one factor or contributing to a factor with a loading less than 0.50, nine of the 16 items remained. Factor analysis results for these nine items are summarized in Table 3. As expected, three factors were identified: [A] peace of mind, [B] loneliness, and [C] concentration. Each consisted of three items, and their Cronbach's alpha coefficients were 0.78, 0.81, and 0.68, respectively, suggesting that these scales have sufficient or acceptable levels of internal consistency.

4.2 Tests of Hypotheses H1 and H2

For each age cohort in treatment and control groups, mean values of two driving outcome variables and three psychological scale scores are shown in Table 4. In young and middle cohorts, the treatment group had a significantly larger mean value of "Time for Completion" than the control group ($p < 0.01$), suggesting that a conversation robot's presence has a protective effect on drivers by significantly increasing their cautiousness. In the same cohorts, however, the robot's presence was not confirmed as significantly decreasing the "Number of Crashes." In the elderly cohort, the robot's protective effect was not identified with respect to "Time for Completion." On the contrary, the "Number of Crashes" was significantly higher in the treatment group (p <

0.05), suggesting that in the elderly cohort, the robot's presence negatively affected drivers' safety.

With regard to psychological scale scores, the young cohort's "peace of mind" was significantly higher ($p < 0.01$), and "loneliness" was significantly lower ($p < 0.1$) in the treatment group than in the control group. In the middle cohort, "concentration" was significantly higher in the treatment group ($p < 0.05$) than in the control group. Finally, the elderly cohort showed no significant difference between treatment and control groups.

Results are summarized as follows:

1) In young and middle cohorts, **H1** was supported as far as cautiousness was adopted as the driving outcomes' index.
2) In the old cohort, **H1** was rejected.
3) In the young cohort, **H2** was supported.
4) In the middle cohort, **H2** was rejected.

4.3 Test of Hypothesis H3

There were three findings for this hypothesis. First, in the linear regression analysis (Table 5), [A] peace of mind was positively associated with "Time for Completion" in the young cohort ($p < 0.1$). Second, this construct was negatively associated with the number of crashes in the elderly cohort ($p <0.05$). Third, although the other two psychological factors were not associated with either of the two driving outcomes, additional analysis (Table 6) implied positive association between [C] concentration and "Time for Completion," even if not linearly. In fact, after the entire sample ($n = 110$) was divided according to [C] concentration and "Time for Completion" and the chi-square test of independence was applied, these two variables were found to be dependent on one another at $p = 0.053$.

Results are summarized as follows:

1) In the young cohort, **H3** was partly supported: [A] peace of mind and [C] concentration contributed to cautiousness.
2) In the middle cohort, **H3** was partly supported: [C] concentration contributed to cautiousness.
3) In the old cohort, **H3** was partly supported: [A] Peace of mind significantly reduced number of crashes.

4.4 Verbal Data Analysis

Table 7 comprehensively lists control group participants' comments about the conversation robot. In the three cohorts, numbers of participants who appreciated the robot's praising function were six (Nos. 1, 2, 3, 7, 11, 13), three (Nos. 3, 8, 10), and two (Nos. 9, 15), respectively. Numbers of participants who appreciated the robot's sympathy, especially when they nearly encountered not-at-fault crashes, were three (Nos. 2, 3, 11), seven (Nos. 1, 5, 7, 14, 17, 18, 20), and one (No. 15), respectively. Numbers of participants who appreciated the robot's accuracy of comments were two (Nos. 16, 17), one (Nos. 11, 13), and two (Nos. 2, 3). Numbers of participants who appreciated the robot's encouragement after crashes were one (No. 14), two (Nos. 6, 9), and one (Nos. 8, 9). Finally, numbers of participants who denied the value of the robot's presence were six (Nos. 5, 7, 8, 9, 15, 17), eight (Nos. 2, 3, 4, 7, 9, 11, 15, 16), and four (Nos. 5, 6, 11, 12).

5. Discussion

This is empirical study demonstrates that the presence of an artificial entity itself, rather than the practical information it provides, has a protective effect on drivers in simulated driving. Specifically, this study has three major findings.

First, in the young cohort, the robot presence significantly affected cautiousness of driving, as measured by time for completing the driving task (**H1**). Taken with the positive effect of the robot's presence on peace of mind (**H2**) and the correlation between cautiousness and peace of mind (**H3**), results suggest the possibility that the robot's presence affected cautiousness via enhancing peace of mind.

Second, as in the young cohort, the robot's presence significantly affected cautiousness in the middle age cohort (**H1**). However, the causal path seems to differ. Considering the effect of the robot's presence on concentration in this cohort (**H2**) and a general correlation between concentration and cautiousness in the entire sample (**H3**), results lead to speculation that the robot's presence contributed to cautiousness via concentration, rather than via peace of mind.

Third, in the elderly cohort, the conversation robot had negative rather than protective effects on drivers. This finding was disappointing, considering the social need to secure elderly drivers' safety.

Two important questions regarding these findings need to be answered. First, why does the presence of a conversation robot encourage cautious driving through different causal paths between young and middle cohorts? Considering the technologically or digitally oriented nature of young generations (e.g., Green & Hannon, 2007; Montogomery, 2009; Savage et al., 2006; McCrindle, 2009), participants in the young cohort might have perceived the conversation robot as quite a natural phenomenon; this might have enabled them to feel “normal” while they drove, thus bringing about peace of mind. This tendency might have been even stronger in the present study because participants in the young cohort were recruited mainly in Kyoto Sangyo University’s faculty of computer science and engineering, to which the second author belongs. This might have prevented young participants from having to scamp their driving tasks. On the other hand, the influence of the robot’s presence on cautious driving via concentration in the middle cohort might be interpreted according to the robot’s role of shifting drivers’ minds after they nearly encountered not-at-fault crashes. Unlike in the young cohort, the robot cannot serve as a natural companion in this cohort. However, it might be that the robot presented itself to drivers’ consciousness only when they encountered risky situations, were shocked, and were addressed by the robot. In other words, the effect of the robot’s talk might be especially strong when critical incidents were not the drivers’ fault and the robot expressed sympathy by affirming that the crash was not the drivers’ fault. This speculation seems partly supported by this cohort’s overrepresented participants, who answered the open-ended question by expressing appreciation for the robot’s sympathy, especially when they nearly had not-at-fault crashes (i.e., seven participants, in contrast to only three participants in the young cohort). The passengers’ role described here could be named *saucers for drivers’ emotions*. To the author’s knowledge, this is the first time that such a passenger role has been mentioned in a scientific paper, regardless of whether passengers are humans or robots.

Second, why did the robot’s presence increase the number of crashes in the elderly cohort? This discouraging finding could be ascribed to overrepresented participants who interrupted experiments due to motion sickness. While 37 participants in treatment and control groups completed driving tasks, as many as 12 interrupted the task and retired due to sickness. This result is consistent with Brooks et al. (2010), who found that older participants had greater likelihood of simulator (motion) sickness than younger participants. Considering this, perhaps even those who completed the driving task felt more or less unwell. In such a situation, at best, the robot's statements were more annoying and distracting. Although this comment did not appear in Table 7 because the participant retired from the driving task, s/he commented, "*After I felt very unwell, I wasn't able to pay attention to the robot's comments*."

These findings have several important practical implications for those who design social robots as an interface between human drivers and driving assistance systems or smart vehicles, or those concerned about drivers' safety in human passengers' presence. The first is for those who seek alternatives to improve young drivers' safety. That young human passengers negatively influence the safe driving of those in the same generation is well documented (e.g., Horvath, Lewis, & Watson, 2012; Preusser, Ferguson, & Williams, 1998, among many). This negative effect is partly ascribed to young passengers' explicit or implicit pressure to engage in speeding (e.g., Horvath, Lewis, & Watson, 2012). The present study's findings suggest that artificial entities can better contribute to young drivers' safety than human passengers, because they are not human, and young drivers do not have a sense of obligation to consider passengers. Practitioners should benefit from focusing on this possibility.

Second, the present study's experimental setting failed to create protective effects for elderly drivers, partly due to prevailing motion sickness. Even so, the finding on peace of mind's influence on decreased crash risks suggests that social robots can have some protective effects on older drivers. The present study cannot suggest specific strategies for enhancing peace of mind of elderly drivers using social robots, but enabling this has profound practical importance.

Third, findings on associations between driving outcomes and drivers' emotions have important implications for human passengers. Drivers benefit from human passengers' presence if those passengers do their best to help with the emotions addressed in the study. Specifically, for young and elderly drivers, it is beneficial for them to drive with peace of mind or comfort, although the passengers' strategy to let drivers do so should depend on drivers' age and personal characteristics. For middle-aged drivers, passengers explicitly expressing sympathy toward drivers is beneficial, especially when drivers feel strain by encountering minor incidents because of other vehicles or pedestrians' errors. This assists drivers in maintaining their concentration, which, of course, protects them. This finding suggests the possibility of a new approach to driving safety, in which the central point is passengers' receiving drivers' emotions, rather than informing and warning drivers, regardless of whether passengers are humans or social robots.

The present study has several important limitations. The first is overrepresented young-cohort participants familiar with computers. In the future, checking findings' generalizability in less biased samples will be important. Notably, however, this biased sample unexpectedly contributed the understanding that familiarity with computers and digital devices might influence association between social robot presence and driving safety. Second, our experimental design was not careful enough to prevent elderly participants' motion sickness, and this might have prevented emergence of this cohort's protective effects. Considering the difficulty of conducting similar experiments in a real setting, in the future, it will be important to design shorter simulated driving experiments that can still identify significant differences between treatment and control groups. Third, the present study aimed to distinguish the protective effect of a social robot's anthropomorphic qualities per se from that of the practicality of the information it gives to drivers, and so we attempted to give only practically irrelevant information to drivers. Overall, this attempt seems to have been successful, considering the frequency of the comments on the uselessness of the robot (e.g., No. 11 of the old cohort, No. 11 of the middle cohort, No. 8 of the young cohort). One participant (No. 2 of the middle cohort) even expressed disappointment that the robot's comments were restricted to retrospective ones. On the other hand, one participant (No. 13 of the middle cohort) appreciated the usefulness of the robot's warnings when s/he did not obey the traffic regulation. Thus, we have to admit the possibility that the identified protective effect is not entirely ascribed to the robot's anthropomorphic qualities per se.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 15K14049.

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Figure 1: Overview of the Driving Simulator System (The depth, width, and height of the robot are 21, 26, and 34 cm, respectively. The degrees of freedom of the head, arms, and body are 3, 1, and 1.)

Figure 2: A scene in the simulated driving course (Event No. 16 as an example. A motor bike behind the bus is entering into the driver's lane in order to turn right at the cross section.)

Figure 3: Conceptual Framework

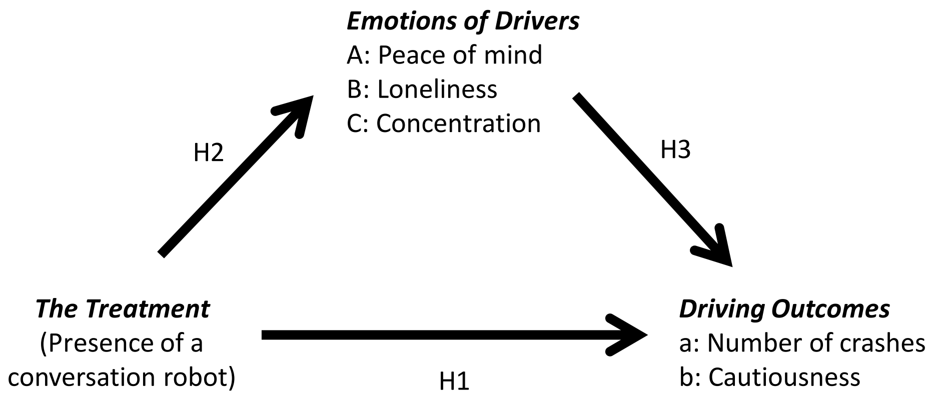

Table 1: The list of events in the scenario constructed on the driving simulator.

Lap	Event No.[1]	Location[2] Absolute	Location[2] Relative	Road Type[3]	Event
1st	1	446	446	A	The driver is supposed to stop at the red light.
1st	2	820	820	A	A truck without the right of way approaches from the left and stops just before entering the intersection.
1st	3 *	1127	1127	A	The driver needs to pass a parked car in the street's first lane.
1st	4 *	1294	1294	A	A car without the right of way enters the intersection from the left.
1st	5 *	1373	1373	A	The driver needs to pass a parked car on the street's first lane.
1st	6 *	1788	1788	A	A car in the opposite lane crosses the driver's lane in order to turn right at the intersection.
1st	7 *	1968	1968	A	The driver needs to pass a parked car on the street's first lane.
1st	8 *	2114	2114	A	A car in the opposite lane swerves from his own lane to pass a truck parked in his lane.
1st	9	2371	2371	A	The driver is supposed to stop at the red light.
1st	10	2749	2749	B	The driver is supposed to stop at the red light.
1st	11	2868	2868	B	The driver is supposed to stop temporarily at the line in front of the intersection.
1st	12	3194	3194	B	The driver is supposed to stop at the red light.
1st	13 *	3429	3429	B	A car without the right of way approaches from the left and enters the intersection.
1st	14	3538	3538	B	The driver is supposed to stop temporarily at the line in front of the intersection.
2nd	15	4021	21	A	The driver is supposed to stop at the red light.
2nd	16 *	4771	771	A	A motor bike in the opposite lane crosses the driver's lane to turn right at the intersection.
2nd	17	5293	1293	A	A bus without the right of way approaches from the left and stops just before entering the intersection.
2nd	18 *	5525	1525	A	A bike flies into the driver's lane from behind a parked car in the first lane.
2nd	19 *	5293	1293	A	A child flies into the driver's lane from behind a parked bus in the first lane.
2nd	20	6371	2371	A	The driver is supposed to stop at the red light.
2nd	21	6585	2585	B	A car is parked at the left hand side of the road.
2nd	22	6686	2686	B	The driver is supposed to stop at the red light.
2nd	23	6930	2930	B	A car without the right of way approaches from the right and enters the intersection.
2nd	24	7194	3194	B	The driver is supposed to stop at the red light.
2nd	25	7328	3328	B	A child flies into the driver's lane from behind a car parked at the left side of the road.
2nd	26	7638	3638	B	The driver is supposed to stop temporarily at the line in front of the intersection.
3rd	27 *	8293	293	A	A motor bike in the opposite lane crosses the driver's lane to turn right at the intersection.
3rd	28	8618	618	A	A truck without the right of way approaches from the left and stops just before entering the intersection.
3rd	29	8898	898	A	The driver is supposed to stop at the red light.
3rd	30	9145	1145	A	A pedestrian nearly, but does not fly into the road from behind a parked car in the first lane.
3rd	31 *	9558	1558	A	A car in the opposite lane swerves from his own lane to pass a truck parked in his lane.
3rd	32 *	9996	1996	A	An elderly driver flies into the driver's lane from behind a parked car in the first lane.
3rd	33	10749	2749	B	The driver is supposed to stop temporarily at the line in front of the intersection.
3rd	34	11193	3193	B	The driver is supposed to stop temporarily at the line in front of the intersection.
3rd	35 *	11501	3501	B	A car without the right of way approaches from the left and enters the intersection.
3rd	36	11639	3639	B	The driver is supposed to stop temporarily at the line in front of the intersection.
4th	37	12446	446	A	The driver is supposed to stop at the red light.
4th	38 *	12919	919	A	A mother and a baby in a car fly into the driver's lane from behind a parked car in the first lane.
4th	39	13294	1294	A	A truck without the right of way approaches from the left and stops just before entering the intersection.
4th	40 *	13771	1771	A	A car in the opposite lane crosses the driver's lane to turn right at the intersection.
4th	41	13968	1968	A	The driver needs to pass a parked car in the street's first lane.
4th	42	14370	2370	A	The driver is supposed to stop at the red light.
4th	43 *	14648	2648	B	A taxi without the right of way approaches from the left and enters the intersection.
4th	44 *	14679	2679	B	A boy and his soccer ball flies out into the road from behind a car parked at the left hand side.
4th	45	14749	2749	B	The driver is supposed to stop temporarily at the line in front of the intersection.
4th	46	15194	3194	B	The driver is supposed to stop temporarily at the line in front of the intersection.
4th	47 *	15353	3353	B	A car without the right of way approaches from the left and enters the intersection.
4th	48	15639	3639	B	The driver is supposed to stop temporarily at the line in front of the intersection.

Notes. 1: In events with an asterisk on their numbers, there is a probability that the driver crashes. 2: Absolute location is the distance [m] driven since the experiment was initiated. Relative location is the distance [m] driven since a new lap was initiated. The distances may include errors (～100[m]) because they were manually identified by the authors based on the information shown on the monitor of the driving simulator. 3: A = Four lane road (with two lanes each way) with the speed limit of 40km/h. B = One lane road with the speed limit of 30km/h.

Table 2: Characteristics of the sample.

	Young Sample (*n* = 38)				Middle Sample (*n* = 39)				Old Sample (*n* = 49)			
	n	%	*M*	*SD*	*n*	%	*M*	*SD*	*n*	%	*M*	*SD*
Gender												
Male	34	89.5			19	48.7			25	51.0		
Female	4	10.5			20	51.3			24	49.0		
Age			22.1	4.5			42.5	6.4			69.6	3.8
Type of Driving License												
Limited to Only AT[1]	16	42.1			9	23.1			2	4.1		
Full License	22	57.9			30	76.9			45	91.8		
Invalid Answer	0	0.0			0	0.0			2	4.1		
Frequency of Driving												
8 = 6-7 Times per Week	2	5.3			17	43.6			15	30.6		
7 = 3-5 Times per Week	0	0.0			14	35.9			18	36.7		
6 = 1-2 Times per Week	8	21.1			8	20.5			16	32.7		
5 = 2-3 Times per Month	4	10.5			0	0.0			1	2.0		
4 = Once per Month	5	13.2			0	0.0			0	0.0		
3 = Once per 2-6 Months	7	18.4			0	0.0			0	0.0		
2 = Once per 7-12 Months	2	5.3			0	0.0			0	0.0		
1 = Other	10	26.3			0	0.0			0	0.0		

Note. 1: Automatic Transmission Vehicles.

Table 3: Factor Analysis Result.

No.[1]	Item	Factors			Cronbach's alpha
		Peace of Mind	Loneliness	Concen -tration	
1	I drove comfortably.	**.86**	-.16		0.78
2	I drove with a sense of security.	**.71**			
3	I drove with a peace of mind.	**.63**	-.18		
4	While I drove, I felt helpless.	-.21	**.75**		0.81
5	While I drove, I was lonely.		**.74**	.20	
6	While I drove, I felt I was alone.	-.15	**.73**	.19	
7	While I drove, I thought about the matter I would attend to later today.	.20	.12	**.76**	0.68
8	While I drove, unrelated matters came to my mind.	.11	.11	**.63**	
9	I got tired of driving on the way.	-.26	.14	**.55**	
	Sum of Square Loading	1.83	1.76	1.36	
	Percentage of Variance Explained	20.4	19.5	15.1	
	Cumlative Percentage of Variance Explained	20.4	39.9	55.0	

Note. 1: The nine items were randomly ordered in the questionnaire.

Table 4: Comparison of driving outcomes between control and treatment groups.

	Young Sample (n = 37[1])			Middle Sample (n = 36[2])			Old Sample (n = 37[3])		
	Treatment (n = 19)	Control (n = 18)	Gap	Treatment (n = 20)	Control (n = 16)	Gap	Treatment (n = 20)	Control (n = 16)	Gap
Driving Results									
Number of Crashes[4]									
M	6.0	6.2	-0.2	6.0	6.3	-0.3	7.4	5.6	1.8 *
SD	3.1	2.8		2.5	2.6		1.9	2.8	
Time for Completion [s]									
M	2292	2089	204 **	2306	2110	196 **	2316	2269	47
SD	298	155		246	212		235	364	
Scale Scores									
Peace of Mind[5]									
M	10.3	7.8	2.5 **	9.4	8.3	1.0	7.9	8.4	-0.5
SD	2.7	3.5		3.4	2.9		2.6	2.6	
Loneliness[6]									
M	6.5	8.6	-2.1 †	5.8	7.0	-1.3	6.4	6.4	0.0
SD	2.5	3.8		3.1	3.3		2.9	3.1	
Concentration[7]									
M	9.1	7.6	1.5	12.0	9.6	2.4 *	11.2	11.6	-0.3
SD	2.7	3.3		2.5	3.4		2.2	2.5	

Notes.†: $p < 0.1$. *: $p < 0.05$. **: $p < 0.01$. **1-3:** These numbers are not consistent with the ones shown in Table 1, because of the loss of data by mistake or the suspention of the experiment due to the motion sickness. **4**: Theoretcal range was between 0 and 19. **5-7**: The theoretical range was between 5 and 15.

Table 5: Regression analysis results explaining driving results in terms of psychological scale scores.

	Young Sample (n = 37)				Middle Sample (n = 36)				Old Sample (n = 37)			
	Number of Crashes		Time for Completion		Number of Crashes		Time for Completion		Number of Crashes		Time for Completion	
Predictive Variables	*beta*	*s.e.*	*beta*	*s.e.*	*beta*	*s.e.*	*beta*	*s.e.*	*beta*	*s.e.*	*beta*	*s.e.*
Peace of Mind	-0.20	0.17	0.28 †	0.15	0.01	0.17	-0.05	0.17	-0.40 *	0.18	0.15	0.23
Loneliness	0.10	0.19	0.09	0.16	0.16	0.18	-0.04	0.18	-0.01	0.18	0.00	0.23
Concentration	-0.17	0.20	0.01	0.17	-0.20	0.17	0.08	0.16	0.20	0.23	0.04	0.29
Model Statistics												
R^2		0.085		0.106		0.085		0.011		0.144		0.015
Adjusted R^2		0.001		0.002		0.001		-0.082		0.066		-0.075

Notes.†: p <0.1. *: p <0.05. **: p <0.01.

Table 6: Contingency Table of Concentration and Time for Completion.

	Time for Completion		**Total by Concentration**
Concentration	< 2500[s]	≧2500[s]	
< 8	22	1	**23**
≧8	68	19	**87**
Total by Time for Completion	**90**	**20**	**110**

Note. Chi-Square for the test of independence between Time for Completion and Concentration was 3.74 (p = 0.053).

Table 7: The comprehensive list of control group participants' comments on the robot

Cohort	No.	Comment
Young	1	I felt good when praised, although I did not reply to the comments.
Young	2	It was good to drive with someone who talks to me. The road was straight and boring, but Phyno kept me cautious. Regarding the content, he praised me or spoke exactly what I felt, and I felt attachment.
Young	3	I was glad to be praised. When he referred to the faults of other vehicles, I felt empathy. He prevents me from getting bored, but it is better if he gives me warnings such as "Pay attention to that car!"
Young	4	Although I was alone, I could concentrate on driving with the help of Phyno. I could drive more cautiously than usual.
Young	5	I was not conscious about the presence of Phyno. I like to listen to music better than to be accompanied by Phyno while I drive.
Young	6	I was at ease with Phyno.
Young	7	Some advice didn't match the situation. I was glad to be praised. In a very few situations, I was distracted by Phyno.
Young	8	Maybe Phyno is not necessary.
Young	9	It was noisy.
Young	10	It was pleasant to drive with Phyno.
Young	11	I was happy to be praised. I felt relaxed when I felt empathy toward what Phyno said.
Young	12	The comments were helpful. I felt as if I could share feelings with Phyno. It was more pleasant than driving alone. It was better if he was engaged in idle talk.
Young	13	I was happy to be praised when I obeyed traffic rules or successfully avoided crashes. This motivated me to continue safe driving. The statements such as "The opposite lane is crowded" was like his monologue, which made me relax.
Young	14	Phyno helped me to switch feelings after failing to avoid crashes and to prepare for the next situation.
Young	15	I could endure loneliness in the presence of Phyno. However, I was surprised when he suddenly started talking.
Young	16	I kept Phyno's comments in my mind, which helped me driver better.
Young	17	It was useful to get feedback. When I concentrated on driving, his voice did not come into my consciousness.
Middle	1	Phyno's presence and its talks were reassuring. I nodded to his monologues.
Middle	2	Phyno helped me to feel peace of mind, but I was at a loss to what extent I should respond to him. It is better if his comments are not restricted to retrospective ones.
Middle	3	When I crashed and received Phyno's comments that followed, I felt like I was corrected. It was not bad to be praised. However, his presence gradually weakened, because of its mechanical comments.
Middle	4	Phyno's presence didn't affect me. I kept driving cautiously, regardless of its presence.
Middle	5	When I almost crashed and said something to myself, I felt as if Phyno was nodding to me. Phyno is useful when driving without passengers.
Middle	6	I was relieved when Phyno encouraged me, but it cannot be my brother.
Middle	7	After getting accustomed to Phyno's statements, I didn't listen to them. I was relieved when I encountered a crash and Phyno said it was not my fault. The voice was not clear. I sometimes felt Phyno was making fun of me.
Middle	8	It was interesting to find myself glad to be praised by Phyno. The voice was charming and never distracting.
Middle	9	Phyno helped me to switch feelings after crashes. At the beginning I was distracted by the voices, but soon I got accustomed to it. I felt he pointed out what I didn't notice, and I calmed down.
Middle	10	The charming voice gave me peace of mind. I was glad to be praised when my driving was successful.
Middle	11	The comments were accurate, but I don't need them, to be honest.
Middle	12	Phyno helped me to have room in my mind. I drove with pleasure.
Middle	13	Phyno made me realize I had not stopped at the red light.
Middle	14	Phyno made me drive cautiously. He praised me and it encouraged me. When he criticized pedestrians flying out into the road, I could not help saying "Yes, I agree!"
Middle	15	I don't have particular impressions toward Phyno.
Middle	16	When I stopped well behind the stop line, restarted, and crossed the line, Phyno thought I failed to stop at the line and corrected me. I got angry. It was noisy.
Middle	17	Knowing it is just a robot, I was glad when he said exactly what I was feeling.
Middle	18	After my first crash, I drove very cautiously. Thus, when my driving was successful, and Phyno praised me, I was glad, after all. When I almost crashed and when Phyno said it was not my fault, I was a little bit relieved.
Middle	19	Thanks to Phyno, I was relaxed while I drove.
Middle	20	I was at ease, especially when Phyno pointed out other vehicles' faults that hindered my safe driving. It was a pleasure to drive with Phyno.
Old	1	It was a pleasure.
Old	2	His observation was accurate.
Old	3	I was relieved. He pointed out what I overlooked, and I was surprised.
Old	4	As I was alone, Phyno's comments were valuable. He made me feel relieved, confident, and peace of mind.
Old	5	I didn't take care of Phyno.
Old	6	Phyno made me feel both relaxed and nervous.
Old	7	It would be better if I could make conversations with Phyno.
Old	8	It was much better than driving alone. I felt at ease, especially after I crashed and Phyno encouraged me.
Old	9	When praised, I felt relaxed. I also felt I was not alone or felt joy. He encouraged me to be careful about the surroundings. Thanks, Phyno!
Old	10	Phyno gave me peace of mind.
Old	11	Phyno's comments were too obvious to deserve attention.
Old	12	Nothing particular.
Old	13	It is not bad to make conversation during driving. It helped me avoid monotony.
Old	14	Without Phyno, I could have driven calmly.
Old	15	Phyno spoke instead of me, and I was relaxed. It was my greatest pleasure to be praised after successfully avoiding crashes.