Trusting Other Vehicles' Automatic Emergency Braking Decreases Self-Protective Driving

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Objective: We focused on drivers in close proximity to vehicles with advanced driver assistance systems (ADAS). We examined whether the belief that an approaching vehicle is equipped with automatic emergency braking (AEB) influences behavior of those drivers.

Background: In addition to benefits of ADAS, previous studies have demonstrated negative behavioral adaptation, that is, behavioral changes after introduction of ADAS, by its users. However, little is known about whether negative behavioral adaptation can occur for nonusers in close proximity to vehicles with ADAS.

Method: Experienced (Experiment 1) and novice (Experiment 2) drivers drove a simulator vehicle without ADAS and tried to pass through intersections. We manipulated participants' belief about whether an approaching vehicle had AEB and time-to-arrival of the approaching vehicle. Participants kept constant speed or pressed the brake pedal before entering each intersection. In Experiment 2, participants rated their trust in AEB by a questionnaire after driving.

Results: In both experiments, belief about the approaching vehicle's AEB did not influence braking probability; however, belief delayed initiation of braking. The effect of belief on braking latency was only observed when trust in AEB was higher in Experiment 2.

Conclusion: Negative behavioral adaptation can occur for nonusers in close proximity to users of AEB, and trust in AEB plays an important role.

Application: When evaluating the effect of ADAS, the possible behavioral change of surrounding nonusers as well as users should be taken into account. To establish consumers' trust accurately, advertisements (e.g., TV commercials) must carefully consider their messages.

Keywords: human–automation interaction, trust in automation, driver behavior, decision making, expert–novice differences

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INTRODUCTION

Advanced driver assistance systems (ADAS), for example, adaptive cruise control (ACC) and lane keeping support systems, have become increasingly popular in Japan (Ministry of Land, Infrastructure, Transport and Tourism, 2018). Indeed, a wealth of research has reported benefits of ADAS, showing that these systems reduce a driver's mental workload (see the review by de Winter et al., 2014).

On the other hand, previous studies have also reported negative behavioral adaptation in ADAS usage. In the context of road safety, behavioral adaptation refers to behavioral changes that occur following the introduction of ADAS (Organization for Economic Cooperation and Development [OECD], 1990). When driving with ACC, compared to driving without ACC, driver behaviors change in various ways. These include delayed reactions to hazardous events (e.g., Larsson et al., 2014; Rudin-Brown & Parker, 2004; Shen & Neyens, 2017) and decreases in minimum time headway (Hoedemaeker & Brookhuis, 1998), as well as decreases in time-to-collision (TTC; Bianchi Piccinini et al., 2015). Additionally, informing drivers about sufficient time gaps between the arrival of their vehicle and that of an approaching vehicle at an intersection decreased the driver's waiting time and the number of stops before entering intersections (Dotzauer et al., 2015).

Despite the fact that negative behavioral adaptation by users of ADAS has attracted focus over a number of years, little is known about how vehicles with ADAS influence nearby nonusers of ADAS (e.g., pedestrians, cyclists, or other drivers without ADAS). If users as well as nonusers engage in less self-protective behaviors after ADAS has been introduced, the expected benefits of ADAS would be discounted more than estimated when only users' negative behavioral adaptation is considered. To evaluate the effect of ADAS on the entire traffic environment, we must examine whether negative behavioral adaptation can occur for nonusers as well as users of ADAS.

Using multidriver simulator experiments, Preuk and colleagues reported that unequipped vehicles' drivers (UVDs) changed their behavior when a lead vehicle was equipped with traffic light assistance systems (Preuk et al., 2016, 2018). When a lead vehicle was assisted by traffic light assistance systems, participants (i.e., UVDs) more smoothly passed through intersections despite receiving no prior information about the lead vehicle's system (Preuk et al., 2016). Even when UVDs received detailed information about the lead vehicle's system, positive behavioral adaptation was still observed (Preuk et al., 2018).

However, when UVDs received detailed information about the lead vehicle's system, the minimum TTC between UVDs and the lead vehicle decreased, compared to when UVDs received no information (Preuk et al., 2018). Preuk et al. (2018) thus raised the possibility that negative behavioral adaptation may arise in UVDs, especially when they are aware that other vehicles are equipped with ADAS.

To understand whether other forms of ADAS may result in negative behavioral adaptation of UVDs, we designed two experiments using automatic emergency braking (AEB) for experienced (Experiment 1) and novice (Experiment 2) drivers. AEB alerts drivers of the vehicle of a possible collision and automatically brakes for imminent collision (Ministry of Land, Infrastructure, Transport and Tourism, 2017). We targeted AEB because it is one of the most popular forms of ADAS in Japan. In 2017, in Japan more than 40% of newly manufactured vehicles equipped with some type of ADAS had AEB (Ministry of Land, Infrastructure, Transport and Tourism, 2018). From 2020, newly manufactured vehicles in many countries will be equipped with AEB (United Nations Economic Commission for Europe [UNECE], 2019). In both experiments, participants tried to pass through nonsignalized intersections. Our main interest lies in the effect of belief that the approaching vehicle has AEB on self-protective behavior.

In Experiment 2, we also focused on the role of trust in AEB. We examined whether the effect of belief that the approaching vehicle has AEB is moderated by trust in AEB, which was inspired by previous research showing a moderation effect of trust in ADAS (e.g., Hergeth et al., 2016; Payre et al., 2016).

Supplementary materials can be accessed at an OSF site (https://osf.io/s3867/).

EXPERIMENT 1

To measure UVDs' behavior in reaction to vehicles with AEB, we created a straight road with nonsignalized intersections on a driving simulator. Participants (i.e., UVDs) were instructed to keep constant speed. Another vehicle approached from a crossroad on the right at every intersection.

We manipulated two within-participant factors. First, participants received instruction beforehand on whether or not this approaching vehicle was equipped with AEB; however, no vehicle actually had any ADAS. Second, to increase the uncertainty of crossing timing, we manipulated time-to-arrival (TTA) of the approaching vehicle at each intersection. Participants then had to decide whether to proceed through the intersection without decelerating, or to press the brake pedal before entering the intersection. We defined their braking response as voluntary self-protective behavior and examined the effect of belief about approaching vehicle's AEB. Our main interest was whether manipulated belief about the approaching vehicle's AEB influenced braking probability and braking timing.

Our hypotheses in Experiment 1 were as follows: by trusting that the AEB of an approaching vehicle would prevent a collision with future moving obstacles, participants would be less likely to brake when they believed that the approaching vehicle was equipped with an AEB. By the same token, the latency before participants pressed the brake would be longer when they believed that the approaching vehicle was equipped with an AEB.

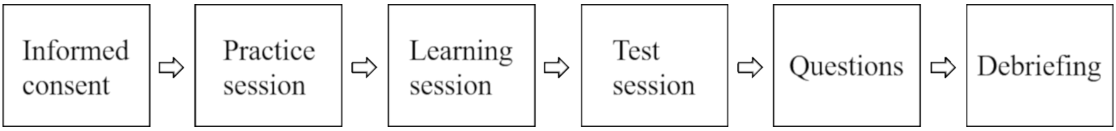

Figure 1. Experimental flows of Experiments 1 and 2.

Method

Experiment 1 was approved by the ethics committees of all authors' affiliations and complied with the American Psychological Association Code of Ethics.

Participants. Thirty-nine experienced Japanese drivers who provided written informed consent participated in Experiment 1 (19 females and 20 males, M = 41.51, SD = 5.35). The number of months they had had their driving licenses ranged between 96 and 379. They reported having, on average, 21.14 years of driving experience (SD = 6.03). The mean driving hours per month was 41.60 (SD = 47.83). Only two participants had experienced how AEB works while driving. According to participant self-reports, all participants had normal or corrected-to-normal binocular vision.

Apparatus. We created a simulated traffic environment using driving simulator software (UC-win/Road Ver.12.0 Driving Sim, FORUM 8 Co., Ltd). The simulated traffic course was displayed on three monitors (42LA6650, LG Electronics Inc.). Each monitor was 42 inches (950 × 560 mm) with a resolution of 1,920 × 1,080 pixels. Participants drove the simulator in a cabin equipped similarly to the driver's seat in an automobile (Compact Research Simulator, FORUM 8 Co., Ltd). Participants could adjust the seat position, so the distance between monitors and participants' eyes was not fixed (approximately 1,300–2,370 cm). A photo of the driving simulator can be seen in the supplementary material 1 (Figure S1).

Procedure. The experiment proceeded according to Figure 1. The experiment comprised three sessions: a practice session, a learning session, and a test session. In the practice session, participants drove on a straight simulated road with no intersections (approximately 2.20 km length). Throughout the practice session, participants accustomed themselves to the braking distance as well as the unusual manner of driving that required them to maintain maximum pressure on the accelerator pedal. Both features were necessary for the forthcoming learning and test sessions. An experimenter instructed participants to follow a lead vehicle by maintaining constant distance headway. At the beginning of the practice session, the lead vehicle initially appeared 50 m ahead and thereafter maintained a speed of 60 km/hr. The maximum speed of the participants' vehicle was set at 60 km/hr; therefore, participants needed to maintain maximum pressure on the accelerator pedal in order to maintain headway distance. At seven predetermined locations, the lead vehicle suddenly decreased its speed to 20 km/hr. The distance between each location ranged between 250 and 350 m. To keep the headway distance constant, participants also needed to decelerate by pressing the brake pedal. After the lead vehicle moved 8 m, it accelerated to 60 km/hr again until the next deceleration location.

Next, in the learning session, participants drove on another straight road with 12 non-signalized intersections and 3 small curves (approximately 6.35 km in total length). Each intersection had a house on the left corner and no other objects (Figures 2 and S3). When a participant's vehicle reached 120 m before each intersection, a vehicle appeared and approached the intersection from a crossroad on the right at a speed of 60 km/hr. According to Japanese traffic rules, in such a road structure, participants had the right to go through the intersection first. The color of the approaching vehicle was red for half of the intersections and blue for the other half (counterbalanced between participants; see Figure S2 and Table S1 in the supplementary material 1). To increase the uncertainty of crossing timing, we manipulated TTA with the approaching vehicle. To this end, there were three possible distances between the initial location and the center of the intersection: 75, 85, or 95 m. Each combination of TTA and color was repeated twice, and their order

Figure 2. Simulated traffic environment in the test session in Experiments 1 and 2. The approaching vehicle's color was red or blue. A pedestrian behind the house (see figure) appeared only once, at the final presentation of an intersection during the test session. The structure of intersections in test and learning sessions was identical, except that the pedestrian never appeared in the learning session.

was predetermined to appear randomly in the 12 intersections (see Table S1 in the supplementary material 1). Participants were asked to keep maximum pressure on the accelerator pedal throughout the learning session (specifically, they kept the speed at 60 km/hr) to control the encounter timing with the approaching vehicle for all participants. In all intersections, the approaching vehicle reached the intersection much earlier than the participant. In 10 out of 12 intersections, the approaching vehicle passed through the intersection without deceleration, whereas it stopped before entering the intersection in the 8th and 10th intersections. Actual behaviors of the approaching vehicles can be seen in movies uploaded to OSF (https://osf.io/s3867/). Throughout the learning session, participants learned that approaching vehicles rarely yielded for the participant vehicles, which increased participants' perceived risk of crossing.

Finally, in the test session, we measured participants' driving behavior. All participants received two instructions. First, for as long as possible they were required to maintain maximum pressure on the accelerator pedal, which was necessary to control the encounter timing with the approaching vehicle for all participants. Second, they could press the brake pedal when necessary, but they were prohibited from engine braking. That is, if they took their foot off the accelerator pedal, they were required to brake; they could not slow the vehicle by only releasing pressure on the accelerator.

In the test session, we manipulated two within-participant factors. The first factor was "belief about AEB." We provided instructions to the participants in order to manipulate their belief about whether or not the approaching vehicle was equipped with an AEB (hereinafter, we call these conditions AEB-equipped and AEB-unequipped, respectively). Each condition was blocked and the order was counterbalanced between participants (Figure 3). At the beginning of each block, participants were notified that approaching vehicles in that block may or may not be equipped with AEB. Importantly, this instruction was deceptive, and none of the approaching vehicles in the test session were actually equipped with any type of ADAS. Preceding the block of trials in the AEB-equipped condition, participants watched on the simulator displays a movie (created by the same simulator software) that allowed them to understand the function of AEB. In the movie, a gray station wagon approached a nonsignalized intersection and a white SUV simultaneously approached from a crossroad on the right. Participants were informed that the SUV was equipped with an AEB. The station wagon entered the intersection first and then suddenly stopped in the middle of the intersection. The SUV kept moving toward it on a collision course but stopped in front of the intersection, as if the AEB prevented the collision. The same event was repeated three times from different viewpoints: a bird's eye view, the station wagon driver's view, and the SUV driver's view.

The second experimental factor in the test session was TTA of the approaching vehicle. As in the learning session, we manipulated TTA only to increase the uncertainty of crossing timing at each intersection; therefore, we were not interested in its effect. There were two TTA conditions in the test session, shorter and longer. The approaching vehicle appeared when

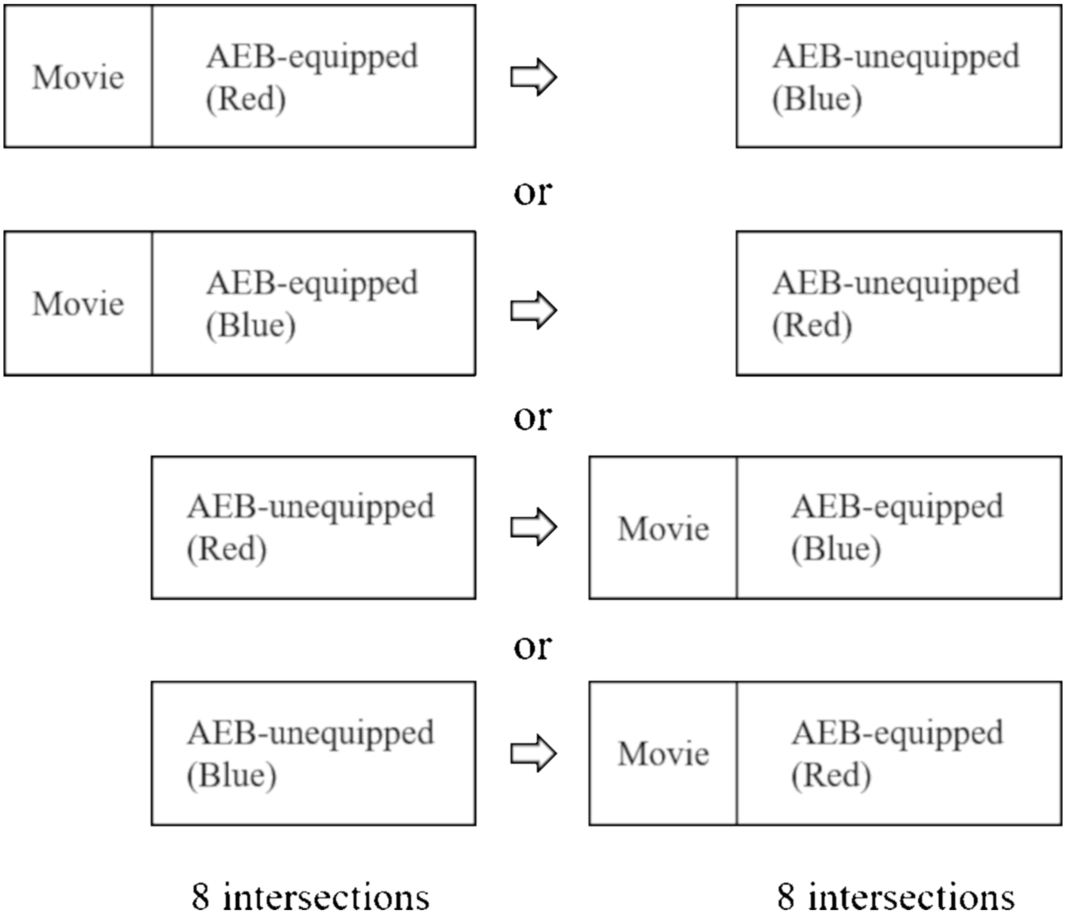

Figure 3. Flow of the test session. AEB-equipped and AEB-unequipped conditions were blocked and the order was counterbalanced. The color of the approaching vehicle (either red or blue) was fixed in the block and also counterbalanced between participants. Therefore, participants were randomly assigned to one of four groups. Preceding the block of the AEB-equipped condition, participants watched a movie that allowed them to understand the function of AEB. AEB = automatic emergency braking.

the participant's vehicle reached 94.5 m before the intersection in the shorter TTA condition and 89.5 m in the longer TTA condition. The approaching vehicle always appeared at a point 95 m away from the center of the intersection (see Table S2 in the supplementary material 1). These TTAs were determined according to pilot experiments in which a collision seemed impending from a participant's viewpoint. Because participants would always reach the intersection slightly earlier than the approaching vehicle if they kept maximum pressure on the accelerator pedal (i.e., maintained 60 km/hr), we defined their braking reaction as voluntary self-protective behavior. Actual behaviors of the approaching vehicles can be seen in movies uploaded to OSF (https://osf.io/s3867/).

Other environments in the test session were the same as that of the learning session, except for three modifications. First, the approaching vehicle suddenly stopped before all intersections and never entered the intersection itself, because we did not want participants to change their driving strategy during the experiment as the result of a collision. Due to shortened TTAs, approaching vehicles soon disappeared from participants' sight as they drove through the intersection. Therefore, participants had little time to figure out that an approaching vehicle always stopped. If participants decelerated or stopped before entering an intersection, they could figure out that the approaching vehicle also stopped. However, because these participants had experienced that the approaching vehicle occasionally yielded in the learning session, we expected that they would not find this unusual.

Second, there were eight intersections with two small curves (approximately 4.27 km in total length) in each belief about AEB condition. In the first intersection, there was no approaching vehicle. In the second to the eighth intersections, a vehicle approached from the right, similar to what participants had experienced in the learning session. The shorter and longer TTA conditions were repeated one after the other (e.g., shorter, longer, shorter, …) and the order was counterbalanced between participants. For ease of distinguishability, the approaching vehicle's color varied between blocks (either red or blue), and this was also counterbalanced (for more details, see Table S2 in the supplementary material 1).

The eighth intersection was included for exploratory investigation of visual attention. Only in the eighth intersection of the second block (i.e., the AEB-equipped condition for half of the participants and the AEB-unequipped condition for the other half), a pedestrian with a white shirt, gray pants, and red shoes appeared behind the house (Figure 2). After the test session finished, to measure awareness of the pedestrian, the experimenter asked participants whether they had noticed anything unusual in the last intersection. If they answered "yes", the experimenter asked them to describe what they had seen, as in Simons and Chabris (1999). If they answered "no," the experimenter asked whether they realized a pedestrian had appeared on the left side of the corner. We do not report on visual attention in the current paper because this task was included only for exploratory purposes.

After all driving tasks were complete, participants answered items on a Japanese-translated version of the Brief Self-Control Scale (Ozaki et al., 2016), a Japanese-translated version of the Driving Behavior Questionnaire (Komada et al., 2009), and the Everyday Attentional Experiences Questionnaire (Shinohara et al., 2007). We used these questionnaires for exploratory purposes, so the results do not include these analyses. Participants also answered questionnaires on demographic information (e.g., age, gender, driving frequency), the color of the remembered AEB-equipped vehicle (red or blue), whether they realized that there were two patterns of TTA in the test session (yes or no), and the degree to which they voluntarily changed behavior depending on the approaching vehicle's AEB (on a 5-point scale from 1 [*not at all*] to 5 [*very much*]).

Finally, the experimenter debriefed participants, informing them that the approaching vehicle's movement had been identical throughout the test session (i.e., no vehicle actually had AEB).

Data analysis. The data log of the driving simulator was recorded at 20 Hz sampling rate. We examined the second to seventh intersections in the test sessions of both AEB conditions. Using time series position data of vehicles, we extracted data between the time an approaching vehicle appeared and the time the participant's vehicle reached the center of the intersection.

For behavioral measures, we coded the occurrence of braking at each intersection (1 = braked, 0 = did not brake) by evaluating whether the input of the brake pedal was greater than zero. If participants pressed down the brake pedal at certain intersections, we calculated braking latency (in seconds) between the time the approaching vehicle appeared and the time the input of the brake pedal first became greater than zero. Therefore, if participants pressed the brake pedal multiple times, we considered only the first braking.

We excluded the entire data set of one participant who incorrectly remembered the color of the approaching vehicle in the AEB-equipped condition, because that participant may have expected that the approaching vehicle had AEB in the AEB-unequipped condition (or vice versa). We also excluded data from three intersections (one from AEB-equipped and two from AEB-unequipped conditions) of another participant who had already pressed the brake pedal before the approaching vehicle appeared in these intersections.

We conducted all analyses using R version 3.5.1 (R Core Team, 2018) and brms package version 2.7.0 (Bürkner, 2017) for the Bayesian estimation of the parameters in each model. We used default priors of brms package in each model. We ran four chains to obtain 30,000 samples of Markov chain Monte Carlo method, respectively, and 5,000 samples from each chain were discarded in the warm-up period. In all models, we judged the convergence across four chains based on $\hat{R}$, Gelman–Rubin convergence statistics (Gelman & Rubin, 1992), and visual inspections of traceplots.

In all regression models, we entered the following variables into predictors: gender (0.5 and −0.5 for female and male, respectively), TTA (0.5 and −0.5 for longer and shorter TTA conditions, respectively), and belief about AEB (0.5 and −0.5 for AEB-equipped and AEB-unequipped conditions, respectively). Our main interest was the effect of belief about AEB. Gender and TTA were entered into predictors as control variables. We considered variations of intercept between participants.

Results

Braking probability. We ran a Bayesian generalized linear mixed model by entering whether participants pressed the brake pedal at each intersection into an outcome variable (1 = braking, 0 = no-braking), which was Bernoulli distributed. The probabilistic model was as follows:

$$\text{Braking}_{ij} \sim \text{Bernoulli}\left(p_{ij}\right)$$

$$p_{ij} = \text{logistic}\left(b_{0j} + b_1\text{Gender}_i + b_2\text{TTA}_i + b_3\text{Belief}_i\right)$$

$$b_{0j} \sim \text{Normal}\left(\mu_2\ ,\ \sigma_2\right)$$

where Braking_{ij} denotes whether participant j pressed the braking pedal at each observation i. b_{0j} denotes a random intercept that was normally distributed with a location parameter $-\infty < \mu_2 < +\infty$ and a scale parameter $\sigma_2 > 0$. b_1 , b_2 , and b_3 are regression coefficients of each predictor. The probability parameter of the Bernoulli distribution, $0 \le p_{ij} \le 1$, is determined by a linear combination of predictors via logistic function.

Mean braking probability was .57 in AEB-equipped condition and .55 in AEB-unequipped condition. As Table 1 shows, the 95% credible interval (CI) of belief about AEB included zero, indicating that belief about the approaching

TABLE 1: Estimated Parameters in Experiment 1

	Predictor	*b* [95% CI]	*SD*	$\hat{R}$
Braking probability				
	Intercept	0.85 [−0.78, 2.61]	0.85	1.00
	Gender	0.03 [−3.35, 3.42]	1.70	1.00
	TTA	−2.66 [−3.51, −1.89]	0.41	1.00
	Belief	0.33 [−0.32, 0.99]	0.33	1.00
Braking latency				
	Intercept	2.00 [1.74, 2.25]	0.13	1.00
	Gender	−0.54 [−1.05, −0.04]	0.26	1.00
	TTA	−0.08 [−0.20, 0.04]	0.06	1.00
	Belief	0.13 [0.01, 0.25]	0.06	1.00

Note. b = expected a posteriori of slope parameter in each model; 95% CI = 95% credible interval; *SD* = standard deviation of the posterior distribution; $\hat{R}$ = Gelman–Rubin convergence statistics; TTA = time-to-arrival; belief = belief about automatic emergency braking.

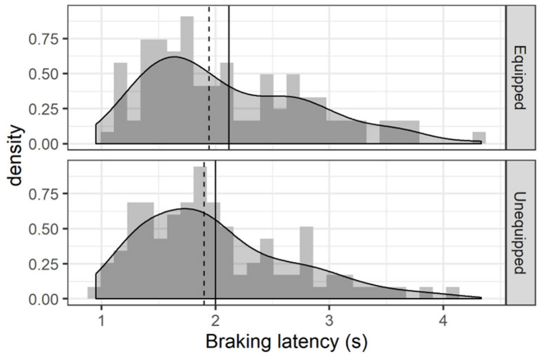

Figure 4. Histograms and density plots of braking latency in Experiment 1 (N = 19). The solid and dashed lines indicate mean and median latency, respectively.

vehicle's AEB did not influence braking probability.

Braking latency. We extracted braking latencies of 19 participants (9 females, 10 males, M = 41, SD = 5.67) who pressed the brake pedal at least once for each combination of AEB and TTA conditions; that is, these 19 participants pressed the brake pedal at least once for all of the following conditions: AEB-equipped and smaller TTA, AEB-equipped and longer TTA, AEB-unequipped and smaller TTA, and AEB-unequipped and longer TTA.

As the histograms and density plots show (Figure 4), distributions of latency had long rightward tails in both AEB conditions. To predict the median rather than the mean, we ran a Bayesian linear quantile mixed model by assuming that braking latency follows an asymmetric Laplace distribution.

The probabilistic model was as follows:

$$\text{Latency}_{ij} \sim \text{Asymmetric\_Laplace}\left(\mu_{1ij}, \sigma_1, \tau\right)$$

$$\mu_{1ij} = b_{0j} + b_1\text{Gender}_i + b_2\text{TTA}_i + b_3\text{Belief}_i$$

$$b_{0j} \sim \text{Normal}\left(\mu_2\ ,\ \sigma_2\right)$$

where $-\infty < \mu_{1ij} < +\infty$, $\sigma_1 > 0$, and $0 < \tau < 1$ were location, scale, and skewness parameters of the asymmetric Laplace distribution, respectively (Geraci & Bottai, 2007). In the current model, to predict the median of braking latency, we set τ to 0.5.

As Table 1 shows, the 95% CI of belief about AEB did not include zero, indicating its effect on braking latency. Braking latency was longer in the AEB-equipped condition than in the AEB-unequipped condition. Participants pressed the brake pedal later in the AEB-equipped condition than in the AEB-unequipped condition.

Voluntary behavioral change. The mean subjective degree of behavioral change for 38 participants (i.e., the number of participants in the braking probability analysis) between AEB-equipped and AEB-unequipped conditions was 2.21 (SD = 1.09), which was below the midpoint of the 5-point scale.

Exploratory analyses. Two participants reported having experienced that AEB worked while they were driving. These participants may have had different trust in AEB or a different driving strategy compared to participants with no prior experience. We repeated the analyses excluding these two participants. As Table S3 in the supplementary material 1 shows, this exclusion had little effect on the results, such that belief about AEB had little effect on braking probability, but braking latency was still longer in the AEB-equipped condition than in the AEB-unequipped condition.

Discussion

Contrary to our hypothesis, the belief that the approaching vehicle was equipped with AEB did not influence braking probability. However, in line with our hypothesis, this belief lengthened braking latency. Because the braking reaction indicates voluntary self-protective behavior, this lengthened braking latency in the AEB-equipped condition suggests a negative behavioral adaptation. UVDs close to the vehicle with AEB made less effort to avoid an accident, as if they had compensated for the improved safety of the approaching vehicle with AEB. Given the low subjective rating of voluntary behavior, we can exclude the alternative account that braking latency was due to demand characteristics (i.e., voluntary behavior along with participant suspicion about the purpose of the experiment).

EXPERIMENT 2

Although Experiment 1 demonstrated that the belief that an approaching vehicle was equipped with AEB reduced self-protective behaviors, this experiment had several limitations. First, all participants were experienced drivers. Many researchers have reported behavioral differences between experienced and novice drivers, such as hazard perception (e.g., Crundall et al., 1999; Gugliotta et al., 2017) and visual search (e.g., Crundall & Underwood, 1998; Underwood et al., 2002). Experienced drivers have advantages in these skills, and therefore, they might have more capacity to take the AEB of approaching vehicles into consideration. In addition, experienced drivers may have more opportunities to be exposed to information about ADAS (e.g., acquiring information about ADAS from car magazines) than novice drivers, and this may have boosted the effect of belief about an approaching vehicle's AEB. Given these differences, we examined whether belief about the approaching vehicle's AEB reduces self-protective behavior of novice drivers as well.

Second, we did not consider individual differences in the trust of AEB. Past research suggests that trust in automation affects human–automation interaction (Lee & See, 2004; Parasuraman & Riley, 1997). Drivers with higher trust in autonomous vehicles took longer to take control of driving the vehicle, that is, switch from autonomous to manual operation (Payre et al., 2016). Higher trust in autonomous driving decreased a driver's attention to automation (Hergeth et al., 2016). However, Bianchi Piccinini et al. (2015) found no correlations between trust in ACC and TTC.

In Experiment 2, we repeated Experiment 1 for novice drivers and measured their trust in AEB. Importantly, we examined "over-trust" in AEB, because it is reasonable to engage in behavioral change based on accurate predictions of the functions. Over-trust means excessive trust in system capabilities (Lee & See, 2004). Excessive trust (i.e., over-trust) can result in uncritical reliance on automation and failure to recognize the limitations of automation or to monitor how automation works (Parasuraman & Riley, 1997). For convenience, we refer to over-trust as trust in the current report.

Our hypotheses were as follows: when participants believe that an approaching vehicle is equipped with an AEB, their braking probability should decrease and braking latency increase. However, trust in AEB should have a moderating effect, and the above effects should be observed only when trust is high.

Method

Experiment 2 was approved by the ethics committees of all authors' affiliations and complied with the American Psychological Association Code of Ethics.

Participants. Twenty-eight novice drivers who provided written informed consent participated in Experiment 2 (11 females and 17 males, M = 20.71, SD = 1.39). All participants were Japanese graduate and undergraduate students. None had participated in Experiment 1. They had 1.14 years of driving experience on average (SD = 1.00). The mean driving hours per month was 2.18 (SD = 2.43). According to their self-reports, all participants had normal or corrected-to-normal binocular vision.

Apparatus. Apparatus and simulated traffic environments were the same as those in Experiment 1.

Procedure. The procedure related to the driving simulator was identical to that in Experiment 1, but the questionnaires differed. The Japanese-translated version of the Brief Self-Control Scale (Ozaki et al., 2016) and the Japanese-translated version of the Driving Behavior Questionnaire (Komada et al., 2009) were used again, but the Everyday Attentional Experiences Questionnaire (Shinohara et al., 2007) was excluded. However, the former two questionnaires were not included in analyses because we used them for exploratory purposes.

Second, we created a new questionnaire addressed to trust in AEB and asked participants to complete it after they answered the question about visual attention toward the pedestrian. Participants rated their agreement with the statements in Table 2 on a 5-point scale (1—*strongly disagree* to 5—*strongly agree*). These items were used to measure "over-trust"

TABLE 2: Questionnaire Items in Experiment 2

	Item
Trust in AEB	
	1. AEB will work correctly, even when the lead vehicle suddenly stops.
	2. If vehicles are equipped with AEB, this will completely prevent traffic collisions.
	3. AEB responds with greater certainty than do humans.
	4. I would like to drive a vehicle with AEB, even if it is expensive.
	5. In many cases, AEB will not work (reverse item).
	6. AEB will prevent accidents, even if pedestrians suddenly run onto the road.
	7. I can drive safely with AEB even when visibility is poor.
Perceived danger	
	1. To what degree did you feel danger at the intersections?
	2. To what degree did you think about other things not related to the experiment?
	3. To what degree did you pay attention to the approaching vehicle at intersections?
	4. To what degree did you feel time pressure while driving?
	5. To what degree did you think an accident might occur at one of the intersections?
	6. To what degree did you feel sleepy while driving?
	7. To what degree could you predict the approaching vehicle's behavior? (reverse item)
	8. To what degree did you feel tired while driving?

Note. AEB = automatic emergency braking.

because most (especially items 1, 2, 3, 6, and 7) represent unrealistic expectations for AEB, considering its current capabilities (Ministry of Land, Infrastructure, Transport and Tourism, 2019).

Third, to compare perceived danger between AEB conditions, participants rated their agreement with the statements in Table 2 on a 5-point scale (1—*not at all* to 5—*extremely*). The target items were (1, 5) and (7), and the others were filler items. Participants answered this questionnaire after rating their belief about AEB condition.

Finally, the experimenter asked participants orally whether they had realized the deception (i.e., actually no vehicle had AEB) at the end of the experiment.

Data analysis. In all analyses, we excluded data of one participant who had pressed the brake pedal before the approaching vehicle appeared in almost all of the intersections of the test session. We also excluded three participants who noticed the deception (i.e., the approaching vehicle was not equipped with AEB even in the equipped condition). Thus data of 24 participants were used for the following analyses. All individuals correctly remembered the color of the approaching vehicle equipped with AEB.

Analyses of behavioral measures were the same as those in Experiment 1 except for additional predictors, namely, trust and interaction between belief about AEB and trust. Trust was calculated as the mean score of seven trust items (Cronbach's $\alpha = .70$). We centered trust before entering it into predictors.

Results

Braking probability. We ran a Bayesian generalized linear mixed model by entering

TABLE 3: Estimated Parameters in Experiment 2

	Predictor	*b* [95% CI]	*SD*	$\hat{R}$
Braking probability				
	Intercept	0.89 [−0.53, 2.38]	0.73	1.00
	Gender	−0.83 [−3.85, 2.03]	1.48	1.00
	TTA	−1.35 [−2.11, −0.64]	0.37	1.00
	Belief	−0.14 [−0.83, 0.56]	0.35	1.00
	Trust	−0.37 [−2.74, 1.87]	1.16	1.00
	Belief × trust	−0.08 [−1.09, 0.93]	0.51	1.00
Braking latency				
	Intercept	1.94 [1.68, 2.21]	0.13	1.00
	Gender	−0.16 [−0.70, 0.38]	0.27	1.00
	TTA	−0.05 [−0.16, 0.06]	0.06	1.00
	Belief	0.15 [0.04, 0.26]	0.06	1.00
	Trust	0.13 [−0.28, 0.54]	0.20	1.00
	Belief × trust	0.29 [0.09, 0.49]	0.10	1.00

Note. b = expected a posteriori of slope parameter in each model; 95% CI = 95% credible interval; *SD* = standard deviation of the posterior distribution; $\hat{R}$ = Gelman–Rubin convergence statistics; TTA = time-to-arrival; belief = belief about AEB; AEB = automatic emergency braking.

whether participants pressed the brake pedal at each intersection into an outcome variable (1 = braking, 0 = no braking) which was Bernoulli distributed. Mean braking probability was .62 in AEB-equipped condition and .63 in AEB-unequipped condition. As Table 3 shows, 95% CIs of the main effect and interaction between belief about AEB condition and trust included zero, indicating that belief about AEB did not influence braking probability.

Braking latency. We extracted braking latencies of 15 participants who braked at least once for each combination of belief about AEB and TTA conditions (4 females and 11 males, *M* = 21.20, *SD* = 1.38). As the histograms and density plots show (Figure 5), the distributions of latency had long rightward tails in both AEB conditions. Therefore, to predict median rather than mean, we ran a Bayesian linear quantile mixed model by assuming that the latency follows an asymmetric Laplace distribution. We recalculated centered trust with 15 participants and entered this recalculation into predictors. As Table 3 shows, the 95% CI of trust included zero, indicating little effect on braking latency. But the 95% CI of belief about AEB did not include zero, indicating its effect on braking latency. Braking latency was longer in the AEB-equipped condition than in the AEB-unequipped condition.

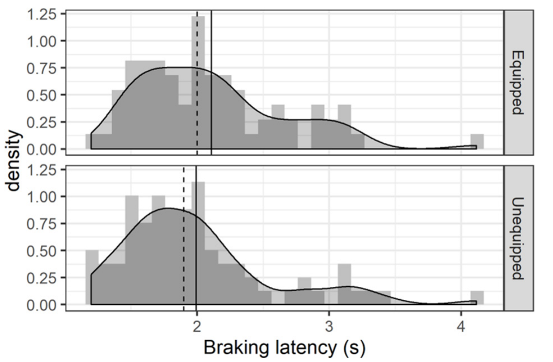

Figure 5. Histograms and density plots of braking latency in Experiment 2 (*N* = 15). The solid and dashed lines indicate mean and median of latency, respectively.

Moreover, the 95% CI of the interaction between AEB condition and trust did not include zero. We then extracted posterior samples and calculated simple slopes. When trust was higher (mean plus 1 standard deviation; namely,

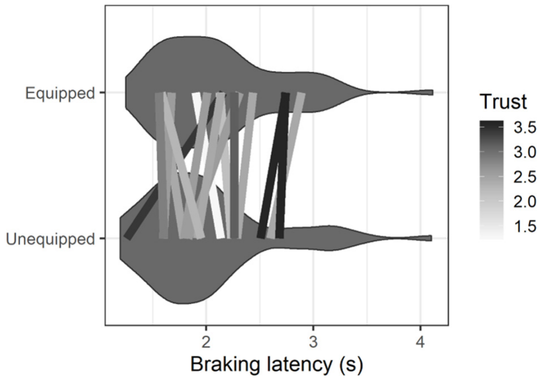

Figure 6. Violin plots and line plots of braking latency in Experiment 2 ($N = 15$). Each line represents mean braking latency of one participant.

centered trust was 0.54), braking latency was longer in the AEB-equipped condition than in the AEB-unequipped condition ($b = 0.31$ [0.15, 0.47]). On the other hand, when trust was lower (mean minus 1 standard deviation; namely, centered trust was −0.54), AEB did not influence braking latency ($b = -0.004$ [−0.16, 0.15]). The relationship between trust and braking latency is displayed in Figure 6.

Voluntary behavioral change. The mean subjective degree of behavioral change between AEB-equipped and AEB-unequipped conditions was 2.29 ($SD = 1.33$), which was below the midpoint of the 5-point scale.

Perceived danger. Scores of three items were averaged (Cronbach's $\alpha = .76$ and .65 in AEB-equipped and AEB-unequipped conditions, respectively). The mean perceived danger scores were 2.81 ($SD = 0.95$) and 2.92 ($SD = 0.87$) in AEB-equipped and AEB-unequipped conditions, respectively. In both conditions, the mean perceived danger was below the midpoint of the 5-point scale.

Discussion

Contrary to our hypothesis, there was little effect of belief that an approaching vehicle was equipped with an AEB on braking probability. However, as predicted, this belief lengthened braking latency. Importantly, as we hypothesized, longer braking latency was observed only when trust in AEB was relatively high. This moderation effect of trust is in line with previous research (e.g., Hergeth et al., 2016). UVDs with higher trust in AEB made less effort to avoid accidents than those with lower trust. This suggests that these UVDs may have compensated for the improved safety of the approaching vehicle equipped with AEB. Given the low subjective rating of voluntary behavioral change between AEB conditions, this result excludes the alternative account that braking latency is due to demand characteristics.

GENERAL DISCUSSION

In the current research, we investigated whether negative behavioral adaptation to ADAS can occur for drivers who are not using ADAS. We examined whether believing an approaching vehicle is equipped with an AEB influences a UVD's driving behavior. We manipulated participant's belief using a block design. In one block, participants believed that all approaching vehicles had AEB, and in the other block, they believed that no approaching vehicles had AEB. Given that newly manufactured vehicles in many countries will be equipped with AEB from 2020 (United Nations Economic Commission for Europe [UNECE], 2019), the comparison between these blocks simulates intraindividual behavioral change before/after all vehicles have AEB.

Experienced drivers may be more likely to experience negative behavioral adaptation than novice drivers because experienced drivers have higher hazard perception and visual search skills (e.g., Crundall et al., 1999; Underwood et al., 2002), as well as more opportunities to be exposed to information about ADAS. However, two experiments revealed that regardless of participants' driving experience, belief about an approaching vehicle's AEB delayed UVDs' braking reactions. These results indicate that exposing to information about ADAS prior to driving facilitates UVDs' negative behavioral adaptation, irrelevant of driving experience.

There are two possible alternative explanations of why driving experience did not interfere with negative behavioral adaptation. First, participants drove on a straight road with few distractions, which might be too simple to reflect the differences between experienced and novice drivers in real-world traffic environments. Second, participants might have driven differently in a driving simulator from how they drive in the real-world traffic environment (e.g., driving more riskily than usual). These factors might have eliminated the possible differences between experienced and novice drivers. We suggest that more naturalistic experiments would allow better insights into the relationship between driving experiences and negative behavioral adaptation by UVDs.

Importantly, in Experiment 2, this negative behavioral adaptation was observed only when trust in AEB was relatively high. In both experiments, the degree of increased braking latency between AEB-equipped and AEB-unequipped conditions was several hundred milliseconds (Tables 1 and 3). Considering that participants maintained 60 km/hr prior to starting to decelerate, delay of braking for several hundred milliseconds results in a shift of several meters in stopping or deceleration, increasing the probability of collision.

Although we observed UVDs' behavioral changes as a result of manipulating belief about the approaching vehicle's AEB, the question remains as to whether these results reflect negative behavioral adaptation. It is also possible that, due to demand characteristics, the participants voluntarily performed according to what they suspected was the purpose of the experiment. Because we manipulated belief about AEB block-by-block, rather than trial-by-trial, participants may have more easily realized that the experimenters were interested in the effect of an approaching vehicle's AEB on their driving behavior.

However, there are three reasons that we believe may rule out an account based on demand characteristics. First, even if participants were aware of our goals, they could not have known about the specifics of the hypothesis (i.e., earlier or later initiation of braking when they received information about the approaching vehicle's AEB). Second, if participants voluntarily changed their behavior to conform to our hypothesis, they should have pressed the brake pedal more frequently; however, belief about AEB had little effect on braking probability. Third, as mentioned in the discussion of each experiment, the mean subjective rating of the voluntary behavioral change between conditions did not reach the midpoint.

It is important to note that the third reason above not only excludes an alternative explanation by demand characteristics, but also gives rise to a question about behavioral change that occurred in spite of the low subjective rating of voluntary behavioral change. One possibility is that delay of braking for several hundred milliseconds might not be large enough for participants to realize. Because this is no more than a post hoc hypothesis and we still do not have any evidence, further research is necessary to examine other alternative explanations.

The current research extends the findings by Preuk et al. (2018). In their experiment, when the lead vehicle was equipped with traffic light assistance systems and participants were informed about the details of this type of system, minimal TTC decreased. This result indicates a negative behavioral adaptation by UVDs who are in close proximity to users of ADAS. Our research contributes new evidence that UVDs' negative behavioral adaptation occurs with a yet unstudied form of ADAS. Moreover, we found that trust determines UVD's negative behavioral adaptation.

Our findings are in line with the concept of cognitive offloading (see the review of Risko & Gilbert, 2016). According to Risko and Gilbert (2016), cognitive offloading is a strategy aimed at reducing cognitive demand by means of offloading it onto the body or into the world. An example of the former is tilting the head to read rotated words (e.g., Risko et al., 2014) and of the latter is writing down to-be-remembered items (e.g., Risko & Dunn, 2015). Negative behavioral adaptation following the introduction of ADAS could be an example of the latter form of cognitive offloading. For example, drivers in highly automated vehicles are less likely to look at the road center compared to drivers in manual vehicles (de Winter et al., 2014). In our experiments, UVDs offloaded risk control onto an approaching vehicle's AEB. Weis and Wiese (2019) showed that use of offloading (i.e., rotating tilted displayed images by manipulating a knob) decreased when individuals received false instructions stating that the knob was less reliable than it actually was. This result suggests that reliance on tools is dependent on trust, which corresponds to our findings in Experiment 2.

The current research provides not only the theoretical contributions above but also practical suggestions. First, the influence of ADAS needs to be examined for UVDs as well as ADAS-users. Even when negative behavioral adaptation does not occur for ADAS-users, if UVDs change their behavior to become more risk-accepting, the benefits of ADAS could be lessened. Similarly, even when ADAS provides benefits for its users, the possibility of negative behavioral adaptation by UVDs should be considered. Second, care needs to be taken in advertising (e.g., in TV commercials) such that this does not enhance excessive trust in ADAS. Payre et al. (2016) reported that the understanding of the system of fully automated driving afforded by rich practice mitigates the negative impact of over-trust. However, because not every driver can experience such extensive practice, it is important to prevent over-trust and to provide an accurate level of trust at the early stage of information acquisition.

Some limitations of the current research should be noted. First, because we did not measure trust for AEB in Experiment 1, it is unclear whether belief about an approaching vehicle's AEB influences braking latency only for experienced drivers with high trust.

Second, in Experiment 2, we recruited novice drivers from young populations. Previous studies (e.g., Crundall et al., 1999; Underwood et al., 2002) recruited participants who had different lengths of driving experience but were similar in age. In contrast, participants in our Experiments 1 and 2 were comparable in terms of both age and driving experience. To understand the effect of UVD driving experience on negative behavioral adaptation, controlling participants' age will be important in future experiments.

Third, the young participants in Experiment 2 did not usually drive (only 2.18 mean driving hours per month), indicating low representativeness of "drivers." To verify the generalizability of the current experiments, especially Experiment 2, not only age but also driving experience should be strictly controlled.

Fourth, in both experiments, almost all participants lacked prior experience that AEB worked while they were driving. Once drivers have experience that AEB works, they may have increased trust in AEB. Conversely, if drivers experience that AEB fails to work when they expect it to work, their trust in AEB may decline. Moreover, having little prior experience could explain the similar results between the two experiments. According to the elaboration likelihood model (Petty & Cacioppo, 1986), those who have little prior knowledge are likely to be persuaded by peripheral information. The short video segment prior to the AEB-equipped condition might have influenced even the experienced drivers in Experiment 1 because of their lack of familiarity with ADAS. To clarify this issue, we suggest that the level of prior experience with AEB should be considered in future research.

Fifth, in both experiments, the control condition was passive rather than active. Participants watched a video segment similar to a TV commercial before the experimental condition (i.e., AEB-equipped condition), whereas they did not watch any video segment in the control condition (i.e., AEB-unequipped condition). Because we did not have an active control condition in which participants watched an irrelevant video segment before the control condition, it is unclear whether there was a mere watching effect on the subsequent driving behavior.

Sixth, in both experiments, participants obtained information about whether or not an approaching vehicle was equipped with AEB; currently this is rare in real traffic environments. Similarly, we could not examine the time-series changes of braking behaviors because of the small number of trials for each belief about AEB condition. Notably, the braking latency was only recorded when participants braked. When UVDs believe that all approaching vehicles have ADAS, they may soon get accustomed to the situation and forget about ADAS. As a result, negative behavioral adaptation may soon diminish. We suggest that the time series of behavioral changes should be examined in future investigations by manipulating the uncertainty about other vehicle's ADAS. More generally, future experiments should be conducted to overcome these limitations of the current research.

In conclusion, we have reported that negative behavioral adaptation is not a user-specific phenomenon in drivers. In this study, believing that an approaching vehicle was equipped with AEB resulted in postponed initiation of braking in drivers who witnessed this approach. More generally, such situations may increase the probability of collisions if the AEB does not function correctly. It is insufficient to consider the extent to which drivers trust an autonomous driving system and how they use it. We must also consider how drivers behave when they encounter vehicles equipped with these types of systems.

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KEY POINTS

- When drivers who did not use any type of ADAS believed that an approaching vehicle was equipped with an AEB, self-protective driving decreased.
- The decrease in self-protective driving was observed only when trust in AEB was relatively high.
- Interventions that either mitigate or prevent the negative effect of over-trust are necessary.

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SUPPLEMENTAL MATERIAL

The online supplemental material is available with the manuscript on the *HF* website.

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