Risk-Taking on Road and in Mind: Behavioral and Neural Patterns of Decision Making between Risky and Safe Drivers

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ABSTRACT

Objective: Drivers' risk tendency is a key issue of on-road safety. The purpose of the present study was to explore individual differences in drivers' decision-making processes, linking external behaviors to internal neural activity, to reveal the cognitive mechanisms of on-road risky behaviors.

Methods: Twenty-four male drivers were split into two groups (risky versus safe drivers) by their self-reported risky driving, measured by the Driving Behavior Questionnaire (DBQ). To assess the drivers' behavioral and neural patterns of decision-making, two psychological paradigms were adopted: the Iowa Gambling Task (IGT) and the Balloon Analogue Risk Task (BART). The performance of each task and corresponding Event Related Potentials (ERPs) evoked by feedback were recorded.

Results: In IGT, both driver groups demonstrated similar capacities to realize the advantage choices (decks with larger expected rewards) through long-term selection-feedback process. However, the risky drivers showed higher preference for the risky choices (decks with identical expected rewards but larger variances) than the safe drivers. In BART, the risky drivers demonstrated higher adjusted pumps than that of the safe drivers, especially for the trials following previous negative feedback. More importantly, the risky drivers showed lower amplitudes of Feedback-Related Negativity (FRN) after negative feedbacks, as well as the lower amplitudes of loss-minus-gain FRN, in both paradigms. The significant between-group difference of P300 amplitudes was also reported, which was modified by specific paradigms and according feedbacks.

Conclusion: The drivers' on-road behaviors were determined by the cognitive process, indicated by the behavioral and neural patterns of decision-making. The risky drivers were relatively less error-revised and more reward-motivated, which were associated with the according neural processing of error-detection and reward-evaluation. In this light, it is feasible to quantize divers' risk tendency in the cognitive stage before actual risky driving or traffic accidents, and intervene accordingly.

INTRODUCTION

Traffic accidents and drivers' risk tendency

According to the World Health Organization report (WHO, 2013), the total number of road traffic deaths is unacceptable high at 1.24 million per year, which equates to nearly 3,400 fatalities on the world's roads every day, with many more being seriously injured. Various countermeasures have been adopted to prevent these on-road tragedies, such as crash-protective vehicle designs, advanced traffic systems, law enforcement, etc. However, drivers' risk tendency and accordingly unsafe behaviors has long been a bottleneck for the improvement of on-road safety (Arthur, Barret, & Alexander, 1991; Gully, Whitney, & Vanosdall, 1995).

On-road risk-taking reflects drivers' inherent motivation rather than their limited capacities in regard to visual-cognition-motor skills. Previous studies of unsafe driving have suggested that violations and errors are two distinct behavior-types (Blockey & Hartley, 1995; Reason, Manstead, Stradling, Baxter, & Campbell, 1990). Violations are defined as "deliberate deviations from those practices believed necessary to maintain the safe operation of a potentially hazardous system", while errors are referred to as "the failure of planned actions to achieve their intended consequences" (Reason et al., 1990). Based on this definition, the Driver Behavior Questionnaire (DBQ) was developed as a survey instrument to measure these concepts of driving behaviors and has since been validated across a wide-range of countries and populations (e.g. Lajunen, Parker, & Summala, 2004; Parker, McDonald, Rabbitt, & Sutcliffe, 2000; Parker, Reason, Manstead, & Stradling, 1995; Xie & Parker, 2002).

Within the scope of driving safety, a considerable number of studies have attempted to propose and validate different models and theories to explain the individual differences of risky driving (Arthur et al., 1991; Conner et al., 2007; Gully et al., 1995; Ivers et al., 2009; Iversen & Rundmo, 2002; Jonah, 1986; Parker, Manstead, Stradling, & Reason, 1992; Ulleberg & Rundmo, 2003). In these researches, various variables were validated as predictors of drivers' risk tendency, such as certain demographics, attitudes, personality traits and risk perception (Arthur et al., 1991; Conner et al., 2007; Parker et al., 1992). For instance, young drivers are at greater risk of being involved in accidents than older drivers as a function of their propensity to take risks (Jonah, 1986); while male drivers demonstrate higher aggression and thrill seeking than female drivers (Turner & McClure, 2003). According to the Theory of Planned Behavior (Ajzen, 2002), subjective attitudes towards traffic safety are related to the violation, aggression and fast driving (Conner et al., 2007; Elliott, Armitage, & Baughan, 2007; Parker et al., 1992; Poulter, Chapman, Bibby, Clarke, & Crundall, 2008). Moreover, drivers' personality traits, e.g. sensation-seeking or normlessness, are also considerable contributors to their risk tendency (Iversen & Rundmo, 2002; Ulleberg & Rundmo, 2003). These risky drivers are also likely to show higher acceptance/lower perceived risks to the hazards in the traffic environment, as compared to safe drivers (Ivers et al., 2009; Ulleberg & Rundmo, 2003). Despite these findings of individual differences on risky driving, the neural basis of drivers' risky decision-making are largely unknown and need to be further explored.

Neural basis of decision-making

As to the decision-making in general situation, a basic function of human brain is identifying and choosing between alternatives based on the perceived utility for providing a positive outcome (gain or certainty) or avoiding a negative outcome (loss or uncertainty) (Hsu, Bhatt, Adolphs, Tranel, & Camerer, 2005; Tom, Fox, Trepel, & Poldrack, 2007). The empirical studies with the measurements of Event-Related Potential (ERP) and Functional Magnetic Resonance Imaging (fMRI) have proved that front limbic brain circuits are activated during this process (Kennerley, Walton, Behrens, Buckley, & Rushworth, 2006; van Veen & Carter, 2002). Especially, Anterior Cingulate Cortex (ACC), located on the medial surface of the frontal lobes, is important for the rational cognition with the function of risk-aversion (Carlson, Zayas, & Guthormsen, 2009; Tom et al., 2007; van Veen & Carter, 2002).

When ACC processes feedback from decision-making, two ERP components, Feedback-Related Negativity (FRN) and P300, demonstrate sensitivity (Carlson et al., 2009; Frank, Woroch, & Curran, 2005; Gold & Shadlen, 2007; Lange, Leue, & Beauducel, 2012; Yeung & Sanfey, 2004). The FRN (approximately 200-300 ms after feedback) is a negative deflection pattern related to an error-detection signal which reflects the violation of reward expectations (Bellebaum, Polezzi, & Daum, 2010). The monitoring system uses this signal to reinforce the learning process, and revise future decision-making (Frank et al., 2005). Thus, more negative FRN amplitude occurs in response to negative rather than positive feedback (Bellebaum et al., 2010; Carlson et al., 2009; Lange et al., 2012). The P300 (approximately 300-400 ms after feedback) is a positive peak pattern related to the reward-evaluation process (Nieuwenhuis, Gilzenrat, Holmes, & Cohen, 2005; Yeung & Sanfey, 2004). The P300 amplitude varies with the motivational significance of feedback information and increases for those individuals who attribute more meaning to that feedback (Carlson et al., 2009).

The evidences from neural studies suggested that the feedback-locked ERP is responsive to individual differences. For example, the people with greater family history of alcohol problems demonstrated smaller amplitudes of FRN after negative feedback (Fein & Chang, 2008). Consistent results of larger amplitude of FRN were also found for the high-risk adolescents when an expected reward did not occur

(Crowley et al., 2009). A reasonable explanation for these findings is that these people who have a propensity to engage in high risk activities are less sensitive to negative feedback. Additionally, a recent study (San Martin, Appelbaum, Pearson, Huettel, & Woldorff, 2013) found that the amplitude of P300 indicated the individuals' behavioral tendencies to maximize gains or to minimize losses. Based on the above results, one may assume that individuals' behavioral differences of risk-taking are rooted in neural processes of decision-making, which can be accordingly identified through ERPs.

Paradigms to identify risky decision-making

To provide laboratory measurements of decision-making, the Iowa Gambling Task (IGT) and the Balloon Analogue Risk Task (BART) are widely used as psychological paradigms that reflect characteristics of risky decision-making.

The IGT (Antoine Bechara, Damasio, Damasio, & Anderson, 1994) is a risk-anticipation task which aims to assess the learning process and anticipate long-term risks in decision-making. During the experiment, participants are required to draw a card from one of four decks (typically displayed on a computer screen). Each card either awards money to the participant, or deducts money from current winnings. Two of the decks (i.e. disadvantage decks) inevitably lead to a long-term loss if one sticks to that deck, even though individual cards might seem to offer high rewards. The other two decks (i.e. advantage decks) result in a net gain if one sticks with that deck, even though individual cards might not seem that profitable. Participants can choose freely from any decks and alternate among the decks, with the explicit goal being to win as much money as possible (which contains the implicit goal of identifying decks with higher long-term rewards). Clinical studies have demonstrated that people with prefrontal cortex impairment will fail to anticipate future outcomes from historical feedback during IGT and continue to pick from the disadvantage decks (Antoine Bechara et al., 1994; A. Bechara, Damasio, Tranel, & Damasio, 1997).

The BART (Lejuez et al., 2002) is another validated paradigm to evaluate risk-taking tendency in the real word. A small balloon accompanied with a pump-button and a collection-button was presented to participants. Within each trial, clicks on the pump-button inflate the balloon incrementally, though the balloon could randomly explode after any pump. When the participant clicks the collection-button, he/she will gain a reward proportional to the size of balloon. If the balloon explodes however, the participant gains nothing. The breakpoint of the balloon was randomly determined for each trial. The studies of BART suggested that the average number of pumps on successful trials (i.e. where the participant collects the reward before the balloon explodes) were sensitive to impulsive sensation seeking and risk-taking in the real world (Lauriola, Panno, Levin, & Lejuez, 2014; Lejuez et al., 2003).

Hypotheses and approaches

The primary aim of this study was to investigate the differences between the risky and safe drivers on the behavioral and neural patterns of decision-making. Two hypotheses were proposed: 1) laboratory behavioral measures of drivers' decision-making are correlated with their on-road behaviors, and self-reported risky drivers make more risks on the two laboratory tasks; 2) the ERP excited by feedback, in terms of FRN and P300, should also differ between risky and safe drivers, which could reflect the neural basis of decision-making and therefore influence driving behaviors. The recruited drivers were classified based on their on-road behaviors rated by the violations aspect of DBQ. IGT and BART were used as the tasks to measure drivers' behavioral patterns of decision-making. While engaging in each task, the feedback-related ERP was recorded to measure the drivers' neural patterns.

METHODS

Participants

Twenty-four male drivers (age from 22 to 28) were recruited from a university population through an online bulletin board. All participants were required to have a minimum of three years' active driving experience (more than one driving per week) with a valid license and more than 15,000 kilometers' total driving distance. Participants were also required to meet additional criteria: right-handed, no history of traumatic brain injury or neurological diseases. Each participant received instructions about the aims and procedures of the experiments, signed the informed consent, and received basic compensation of RMB 120 Yuan (approximately 20 U.S. dollars) and additional payment based on the total rewards obtained on IGT and BART.

Experimental task and measurements

IGT and behavioral measurements

IGT in present study was modified based on the original version (Antoine Bechara et al., 1994), adapted for ERPs analysis. This modified IGT consisted of four blocks (50 trials in each block, 200 trials in total) to obtain enough evoked ERPs. The participants were instructed to maximize the total rewards through selections from four card decks and they could choose freely from any decks and alternate among the decks for each trial.

The detailed trial sequence of IGT is illustrated in Figure 1. The four decks involved four choices of different characteristics: A- disadvantage and low-risk (50% chance to gain 10 score, 50% chance to lose 15 score), B- disadvantage and high-risk (90% change to gain 10 score, 10% chance to lose 115 score), C- advantage and low-risk (50% chance to gain 5 score, 50% chance to gain 0 score), D- advantage and high-risk (90% chance to gain 5 score, 10% chance to lose 20 score). The disadvantage decks would result in overall losses for participants sticking with them over the long term (expected reward equal to -2.5 score for each trial), while the advantage decks produced a positive gain over the long term (expected reward equal to -2.5 score for each trial). The low-risk decks were of smaller variances (frequent but small losses) for the long-term selections, while the high-risk decks were of larger variances (occasional but large losses). There was no difference on the expected rewards between A and B, or between C and D. During each trial, the participants were instructed to select one in four decks by pressing keyword buttons marked with A, B, C and D. Each selection was followed by an immediate display of feedback with total budget. The percentages of different choices on each block were recorded to reflect participants' learning process and preference of decision-making.

BART and behavioral measurements

For this study the BART (Figure 1) was based on the original version developed by Lejuez et al. (2002). Four items were present to participants during testing: a small balloon, a pump-button, a collection-button and a display to show the number of pumps made in the current trial and total budget. Within each trial, the participants were instructed to press keyword buttons alternatively (marked with "pump" and "collect" accordingly) to pump the balloon, or collect rewards equal to the number of pumps made in the current trial.

After each pump, the balloon increased its size proportionally in each direction. Each balloon had a random explosion point obeying a uniform distribution, from 1 to 10. Thus, the probability that the balloon would explode was fixed at 1/10 for the first pump. If the balloon did not explode after the first pump, this probability changed into 1/9 on the second pump, and became certainty (i.e. 1/1) after the ninth pump. According to the algorithm of Lejuez et al. (2002), the average breakpoint of explosion was 5 pumps. If a balloon was pumped past its explosion point, the display showed an exploded balloon and the reward of this trial was zero.

The aim of participants in the BART task was to maximize the total rewards by increasing the pumps before collection while limiting the number of trials ending in an explosion. They did this through 80 trials (4 blocks, with 20 trials in each block). The number of adjusted pumps (the average number of pumps on successfully collected trials) was calculated to reflect participants risk tendency. Additionally, to explore the effect of historical feedback on participants' current decision-making, the adjusted pumps were calculated from two types of trials: the trials following a successful collection trial or following an explosion trial.

<Figure 1>

Feedback–locked ERPs: FRN and P300

Electroencephalogram (EEG) was recorded via tin electrodes mounted in an elastic cap (NeroScan Inc., USA) from three electrodes: FZ, FCZ and CZ, according to sites of International 10/20 system. Eye blinks were recorded from right supraorbital and infraorbital electrodes for artifact reduction. The electrodes at left/right mastoids served as the reference points and the GND electrode on the cap served as ground. All EEGs were recorded at the simple rate of 1,000Hz and referenced to the averaged voltage of mastoids. During recording, the impedance of all electrodes was kept below 10kΩ.

Recorded EEGs were first amplified with a 0.1-30Hz band pass. Ocular artifacts and other aberrant signals were deducted through the off-line analysis of Curry 7 (NeroScan Inc., USA) with a ±100μV threshold. The EEG epochs (800ms: from 200ms pre-feedback to 600ms after feedback) were then extracted and averaged to obtain feedback-locked ERPs. Consistent with previous studies (Wu & Zhou, 2009; Yeung & Sanfey, 2004), the FRN and P300 were measured by the mean amplitudes within the fixed time windows. In this study, the FRN amplitudes were averaged from 200-300ms post-onset of feedback, and P300 amplitudes were averaged from 350-450ms periods.

Procedure

Upon arrival to the laboratory, participants were required to complete the DBQ with the appended questionnaires to gather their on-road behaviors, demographics and driving experience. The version of the DBQ for this study was based on the 33-item version (Lajunen et al., 2004), containing 11 items to measure drivers' risky driving (i.e. ordinary and aggressive violations). DBQ-violation was rated by the five-point Likert scale, from 1- "not conducted this risky behavior at all", to 5- "always conducted this risky behavior".

During the experiment, participants were instructed to gain as great a total reward as possible during IGT and BART. The experimental tasks were displayed by E-prime (Psychology Software Tools, Inc., USA) in a 19inch monitor, 60cm in front of the participants. Before the formal tasks, participants were allowed to perform a training sessions to familiarize with the display and control. The training sessions contained 20 trials for IGT and 10 trials for BART, with exactly the same appearance as formal tasks but faked feedbacks. During formal tasks, the participants' decisions and ERPs to feedback were recorded simultaneously. After they had finished all tasks, the participants were provided with monetary rewards, equal to (total score of IGT + adjusted pumps of BART)/100 Yuan, as additional payment.

Experiment design and statistical methods

To explore the individual differences on the behavioral and neural patterns between risky and safe drivers' decision-making, a mixed design was adopted. The between-group factor was drivers of high/low on-road risk tendency. At the behavioral level, percentages of IGT choices and adjusted pumps of BART were examined, considering the four blocks as a within-group effect to evaluate the learning effect of through historic feedback. At the neural level, the amplitudes of FRN and P300 were analyzed, with electrode position forming a further within-subjects variable (FZ, FCZ and CZ). The statistical analysis was conducted with repeated-measures ANOVA in R (version 3.0.3). The significant main effect of independent variable was decomposed via post-hoc t-test comparisons, adjusted with a Bonferroni correction.

RESULTS

Split of risky and safe drivers

To divide the drivers according to their on-road risk tendency, participants were classified depending on whether their scores fell above or below the median of DBQ-violation score (equal to 26.5). The average score for risky drivers was 33.4 (SD= 3.1), and average score for safe drivers was 21.2 (SD= 2.1). Independent *t* tests were conducted to examine whether demographics and driving experiences differed between the two groups (See Table 1). The only significance was reported for the number of self-reported violations ($t = 1.59, p = .03$), which suggested that drivers in the risky group engaged in more frequent risky driving than drivers with lower DBQ-violation scores.

<Table 1>

Percentage of the IGT choices

At the behavioral level of IGT, both risky and safe drivers were generally risk-averse and modulated their decisions according to reward history (see Figure 2). All participants were able to recognize the difference of expected rewards across different decks, and accordingly decreased the number of cards taken from disadvantage decks (A and B) and increased number of cards taken from advantage decks (C and D). The main effect of block was found for the percentages of A ($F_{(3,66)} = 6.61,\ p < .01$), B ($F_{(3,66)} = 7.52,\ p < .01$), C ($F_{(3,66)} = 9.73,\ p < .01$) and D ($F_{(3,66)} = 2.81,\ p = .04$). Despite risky drivers appearing to choose more cards from the risky decks and less cards from safe decks compared to the safe drivers, the between-group difference of each single deck was not supported by the statistical analysis (A ($F_{(1,22)} = 0.79,\ p = .38$), B ($F_{(1,22)} = 2.74,\ p = .11$), C ($F_{(1,22)} = 3.18,\ p = .09$), D ($F_{(1,22)} = 2.12,\ p = .15$)). As to the percentage of advantage-minus-disadvantage choices, the effect of block showed significance ($F_{(3,66)} = 22.52,\ p < .01$), but no notable difference was established between the two groups. The only significant between-group difference was the percentage of safe-minus-risky choices ($F_{(1,22)} = 4.83,\ p = .04$) with risky drivers having a lower percentage than safe drivers. Both groups however increased safe-minus-risky choices in the subsequent block than earlier block ($F_{(3,66)} = 3.09,\ p = .03$).

<Figure 2>

Adjusted pumps of BART

A between-group effect was found with the adjusted pumps measure ($F_{(1,22)} = 3.42, p = .02$) with risky drivers making an average of 4.8 pumps on successful trials, while safe drivers made only 4.3 pumps on average (see Figure 3). There was no significant effect of block and group×block interaction. When the BART trials were divided according to the feedback (collection or explosion) of previous trial, the adjusted pumps after collection were higher than adjusted pumps after explosion. An interaction was also noted between driver group and previous feedback: although there was no between-group difference for the adjusted pumps following a successful collection trial, the decrease noted for the adjusted pumps after an explosion was significantly greater for the safe drivers compared to the risky drivers ($F_{(1,22)} = 5.61, p = .03$). No significant effect of block and group×block interaction was reported on the adjusted pumps after either collection or explosion.

<Figure 3>

FRN and P300

Figure 4 presents the IGT ERPs on negative (loss, solid line) and positive (win, dashed line) feedbacks at the electrodes of FZ, FCZ and FC for the advantage, disadvantage, safe and risky choices. The 2 (group: risky and safe drivers) ×8 (feedback: advantage decks-loss/win, disadvantage decks-loss/win, risky decks-loss/win, safe decks-loss/win) × 3 (electrode: FZ, FCZ and FC) repeated-measures ANOVA was conducted. The amplitudes of FRN significantly differed between the groups ($F_{(1,504)} = 5.69,\ p < .01$) and the group×feedback interaction was also significant ($F_{(7,504)} = 4.42,\ p < .01$). The FRN amplitudes of risky drivers were significantly lower ($p < .05$) than that of safe drivers for all negative feedbacks (advantage loss, disadvantage loss, safe loss and risky loss). No significant between-group difference of FRN amplitudes was reported for the positive feedbacks. The P300 amplitudes were significantly affected by the group ($F_{(1,504)} = 2.51,\ p = .01$), feedback ($F_{(7,504)} = 4.11,\ p < .01$) and their interaction ($F_{(7,504)} = 2.42,\ p = .02$). The P300 amplitudes of risky drivers were significantly higher than that of safe drivers in disadvantage-win ($p = .02$) and risky-win ($p < .01$). Meanwhile, the P300 amplitudes for positive feedbacks were significantly higher ($p < .01$) than that for the corresponding negative feedbacks for both groups. Additionally, FRNs and P300 did not significantly differ across electrodes of FZ, FCZ and CZ during IGT.

<Figure 4>

Figure 5 shows the BART ERPs on negative (explosion, in solid line) and positive (collection, in dashed line) feedbacks at the electrodes of FZ, FCZ and CZ. The 2 (group: risky and safe drivers) × 2 (feedback: collection and explosion) × 3 (electrode: FZ, FCZ and FC) repeated-measures ANOVA was conducted. The FRN amplitudes were significantly affected by group ($F_{(1,126)} = 11.54,\ p < .01$), feedback ($F_{(1.126)} = 65.22,\ p < .01$) and produced a significant interaction ($F_{(1,126)} = 4.67,\ p = .03$). The FRN amplitudes of risky drivers were significantly lower ($p < .01$) than that of safe drivers for negative feedbacks. No significant between-group difference of FRN amplitudes ($p = .19$) was reported for positive feedbacks. The significantly higher ($p < .01$) FRN amplitudes occurred at the negative feedbacks rather than the positive feedbacks for both groups. The P300 amplitudes were significantly affected by feedback ($F_{(1,126)} = 4.11,\ p < .01$) and group×feedback interaction ($F_{(1,126)} = 6.34,\ p < .01$). The P300 amplitudes of negative feedbacks were significantly higher ($p < .01$) than that of positive feedbacks, and this difference was smaller for risky drivers than safe drivers. No significant main and interaction effects of electrodes were reported on either FRN or P300 during BART.

<Figure 5>

Differences of neural responses between negative and positive feedbacks

The results of the behavioral measures have demonstrated that self-reported risk-taking during driving relates to performance on two decontextualized measures of risk taking. Risky drivers showed higher probabilities for choosing from risky decks in the IGT (significant for the percentage of safe-risky choices), and made more pumps on average on successful BART trials. One possible interpretation of these findings is that the high-risk individuals might differ from the low-risk individuals on the responses to losses versus gains (Crowley et al., 2009; Fein & Chang, 2008). To assess this assumption, the loss-minus-gain amplitudes of FRN and P300, which were calculated by ERPs of negative feedbacks minus that of positive feedbacks, were compared between two groups across varied decision types respectively (detailed in Figure 6). Since no significant effects of the electrodes were reported, the ERPs used here were averaged from FZ, FCZ and CZ.

For all decisions in IGT and BART, the amplitudes of FRN evoked by negative feedbacks were larger on average (more negative-going) than those evoked by positive feedbacks. Moreover, the loss-minus-gain FRN amplitudes were smaller for risky drivers than those of the safe drivers, which demonstrated the significances in IGT-advantage ($p < .01$), IGT-disadvantage ($p = .03$), IGT-risky ($p < .01$) and BART ($p < .01$).

However, in regard to P300 amplitudes, negative feedback evoked smaller positive-going voltage than the positive feedbacks in IGT, and evoked larger positive-going voltage in BART. Additionally, the differences of loss-minus-gain

P300 amplitudes between two groups were also modified by the specific paradigms and according decision types. The loss-minus-gain P300 amplitudes of the risky drivers, as compared to the safe drivers, were significantly larger in IGT-advantage ($p = .04$) and IGT-risky ($p = .05$), and were significantly smaller in BART ($p < .01$).

DISCUSSION

The aim of this study was to examine the individual difference of decision-making between risky and safe drivers in terms of behavioral and neural responses. Two psychological paradigms, IGT and BART, were adopted for this purpose. The results failed to reject the hypotheses that the laboratory measurements of behavioral and feedback-related ERP responses across varied decontextualized decision types were associated with drivers' DBQ-violation scores and corresponding self-reported on-road risky behaviors.

At the behavioral level, the risky drivers, whose DBQ-violation scores were above the median score, showed lower percentage of safe-risky choices in IGT, and also demonstrated more pumps during BART. During IGT, although both risky and safe drivers had the similar capacities to identify the decks with higher expected rewards (advantage choices: C and D) through a long-term learning of selections and feedbacks (A. Bechara et al., 1997), the risky drivers demonstrated greater preference for the risky decks than safe drivers. Compared with safe decks (A and C), risky decks produced identical expected rewards but higher reward variances, which suggests drivers with a high on-road risk tendency are more likely to tolerate the options of uncertainty. During BART, the adjusted pumps (i.e. average number of pumps in trials ending with collection) were significantly higher for the risky drivers than that for safe drivers, which implies that the impulsivity and sensation-seeking assessed in BART may reflect similar characteristics on the road (Lauriola et al., 2014; Lejuez et al., 2002). When the trials were divided by the outcomes of previous trials (either an explosion or a successful collection), the results suggested the between-group difference on total adjusted pumps was mainly due to the higher adjusted pumps after explosion for the risky drivers. The risky drivers were less likely to revise the current risky decision-making (balloon pumps) according to the historic negative feedback (explosions) than the safe drivers.

At the neural level, the feedback-locked ERPs, in terms of FRN and P300 amplitudes, were qualified by the between-group effect, correlating with the feedback types of specific paradigms. Consistent with previous studies (Bellebaum et al., 2010; Crowley et al., 2009; Frank et al., 2005; Lange et al., 2012), the FRNs were present in approximately 300ms after the feedbacks, and visually more negative-going for negative than positive feedbacks in either IGT or BART. More importantly, the universal between-group difference of FRNs was demonstrated for both paradigms, which suggested that the amplitudes of negative-feedback-related FRN for risky drivers were significantly lower than those of safe drivers. As for the P300, the amplitudes of positive and negative feedbacks were differentiated by the specific paradigms. For both groups of drivers, the P300 amplitudes relating to positive feedback were significantly higher than those relating to negative feedback in the IGT, and were significantly lower in the BART. The between-group difference of P300 also differed between two paradigms. In comparison with safe drivers, the risky drivers demonstrated higher amplitudes of P300 to positive feedback in the IGT with significance effects noted for the disadvantage and risky decks, though no differences were noted in the BART.

As demonstrated by the behavioral measures, the risky and safe drivers showed different patterns of decision-making in two long-term selection paradigms. One intuitional explanation for these findings was the individual differences of cognitive response to the negative-versus-positive feedbacks (Crowley et al., 2009; San Martin et al., 2013). On this basis, the between-group comparisons on the loss-minus-gain amplitudes of FRN and P300 provide an alternative perspective. The risky driver showed smaller (negative-going) loss-minus-gain FRN amplitudes with significances in all feedbacks expect for the IGT-safe decks, which suggested that they were generally less sensitive during the error-detection process than the safe drivers (Bellebaum et al., 2010; Frank et al., 2005; van Veen & Carter, 2002). In terms of P300 amplitudes, the IGT paradigm evoked more pronounced component at gains. However, BART paradigm evoked more pronounced component at losses. The between-group difference of loss-minus-gain P300 amplitudes was varied across paradigms and decision types. The risky drivers demonstrated significantly larger (more negative-going) loss-minus-gain P300 amplitudes at IGT-advantage and IGT-risky decks and smaller (less positive-going) loss-minus-gain P300 amplitudes with the BART. Given that the P300 could indicate the motivational significance of engagement during reward-evaluation (Carlson et al., 2009; Lange et al., 2012; San Martin et al., 2013; Yeung & Sanfey, 2004), it is reasonable to suggest that the risky drivers engaged more attention resources in the win conditions of IGT-advantage and IGT-risky decks than the safe drivers, and were correspondingly less engaged in the loss conditions of the BART. Combing these findings with the behavioral patterns mentioned above, the risky drivers' decision-making was relatively insensitive to the losses, and highly motivated by the rewards.

Limitations

To the best of our knowledge, this is the first study to examine the individual differences on the behaviors and underlie neural processes of decision-making among drivers differentiated by on-road risk tendency. To exclude other possible individual factors, our samples were selected from the young male drivers of university population. Since previous studies had reported that several individual contributors, such as gender and age, were significant to the decision-making (Crowley et al., 2009; Lauriola et al., 2014) and driving behaviors (Ivers et al., 2009; Iversen & Rundmo, 2002; Turner & McClure, 2003; Ulleberg & Rundmo, 2003), the larger and more representative simples could be necessary for generalizing these findings to the universal populations. The main effects of feedbacks on neural responses were reported in this study. Since several studies have detailed the neural variances to feedback with varied valence, magnitude and expectancy (Carlson et al., 2009; Wu & Zhou, 2009; Yeung & Sanfey, 2004), more sophisticated discussions on this issue are beyond the primary scope of this study. However, it should be noted that the individual differences on ERPs, especially for the P300 components, were largely determined by the specific decision paradigms.

CONCLUSION

The findings of this study demonstrated that drivers with high/low on-road risk tendency differed in their patterns of decision-making, as indicated by both behavioral and neural measures. Although both risky and safe drivers could recognize the high-rewards options during the long-term selection-feedback process, the risky drivers showed more preferences to the choices with larger variances (detailed in the percentage of IGT choices). In addition, the risky drivers also took risks more frequently for the higher rewards and appeared less influenced by previous negative feedback (detailed in the adjusted BART pumps). Underlining the cognitive process, the risky drivers showed lower evoked neural responses to the negative feedbacks (smaller loss-minus-gain FRN amplitudes in both IGT and BART, smaller loss-minus-gain P300 amplitudes in BART) and were more highly motived by the positive feedbacks (larger loss-minus-gain P300 amplitudes in IGT).

These findings have several important implications to explain the cognitive mechanism of on-road risky behaviors. First, the drivers' on-road risk-taking as measured by self-reported DBQ-violations appears linked to neural and behavioral patterns in context-free environments. Secondly, the risky drivers were relatively less concerned with errors and were more reward-motivated than safe drivers during decision-making, which was associated with their according neural processing of error-detection and reward-evaluation. During daily driving, drivers make various decisions to optimize the balance of efficiency and safety, qualified by the individuals' subjective appraisals. Thus, for more effective countermeasures to reduce risky driving, one useful approach might be to identify divers' risk tendency at the stage of cognition rather than after actual risky behaviors and intervene beforehand.

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List of Tables

Table 1 Distribution of demographics and driving experience of risky and safe drivers

Variables	**Risky drivers (n=12)**	**Safe drivers (n=12)**	***t***	***p***
Age	24.5 (2.2)	23.6 (1.1)	1.32	0.21
Education [a]	2.2 (0.8)	1.8 (0.9)	1.19	0.25
Driving frequency(times per week)	2 (1.0)	2.5 (0.9)	1.25	0.22
Years of driving	4.9 (1.1)	4.9 (0.8)	0.01	1.00
Annual distance of driving (km)	4792.0 (2189.4)	4958.1 (1912.4)	0.20	0.84
Violations(times in recent three years)	3.1 (3.0)	0.8 (1.3)	2.32	0.03
Accidents (times in recent three years)	0.4 (0.5)	0.3 (0.6)	1.59	0.12

a Education: 1-high school, 2-bachelor, 3-master, 4-docator

Note. Standard Deviations are showed in brackets

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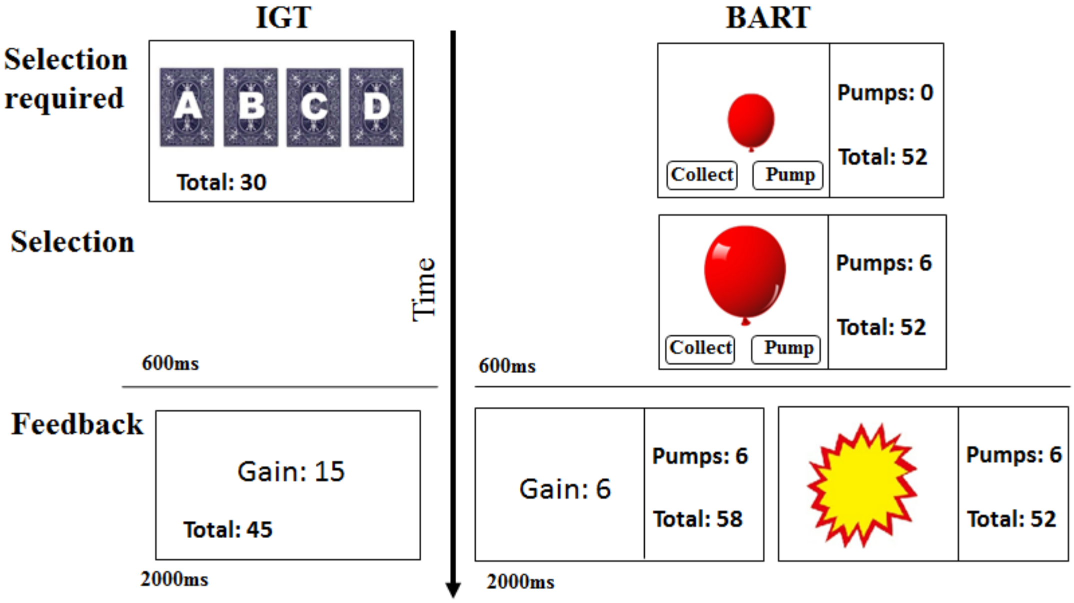

Figure 1 Trial sequence of IGT and BART. The feedbacks for both paradigms were presented at 600ms after participants' selections, and lasted for 2000ms

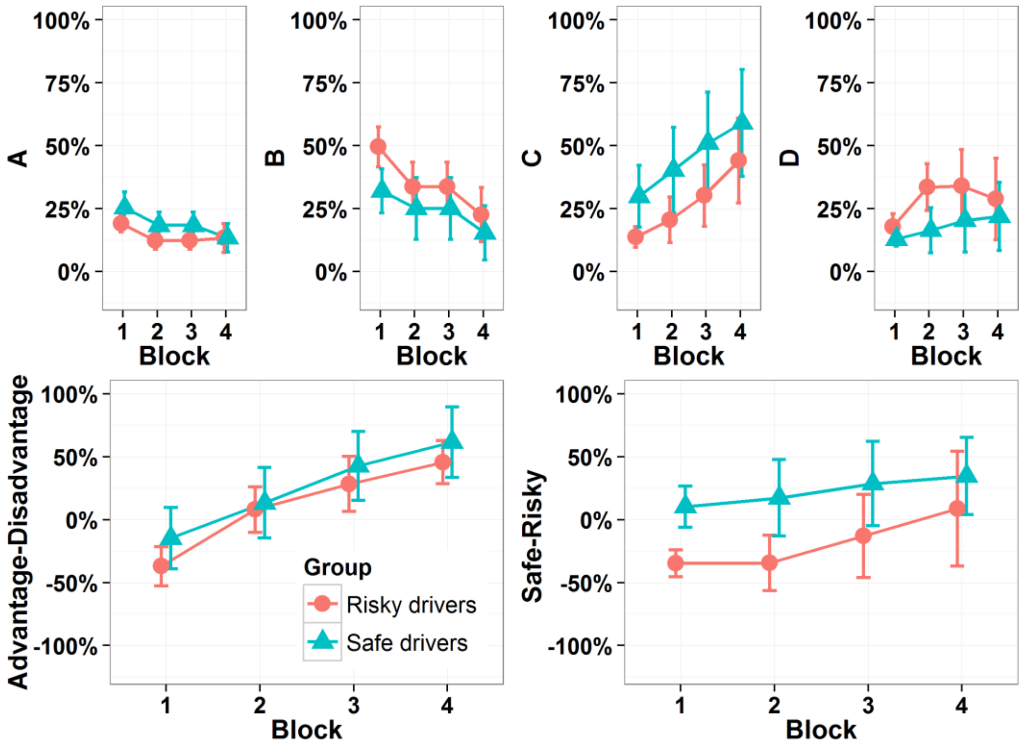

Figure 2 Percentages of IGT choices across blocks. Error bars depicted standard deviations

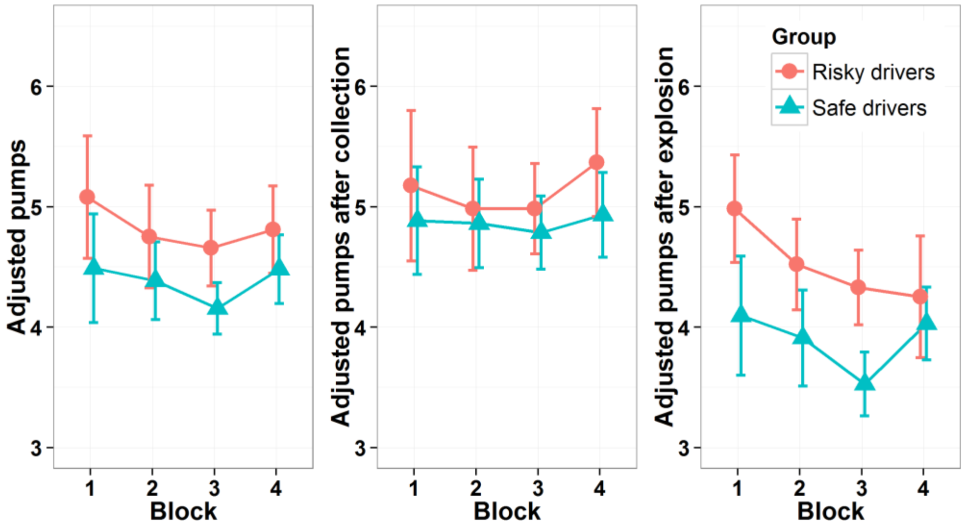

Figure 3 Adjusted pumps of BART across blocks. Error bars depicted standard deviations

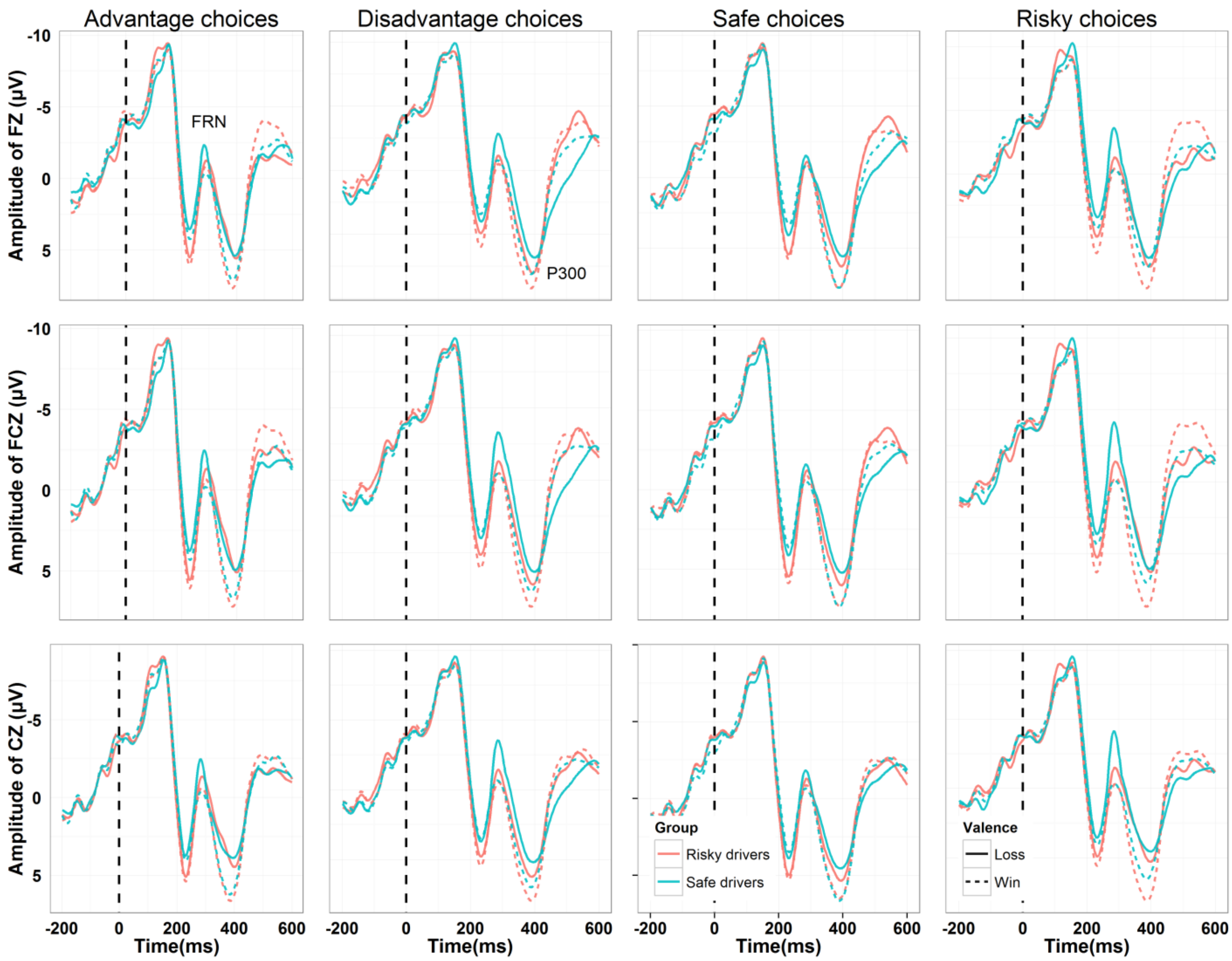

Figure 4 Grand-average ERP of IGT for risky and safe drivers across feedbacks and electrodes

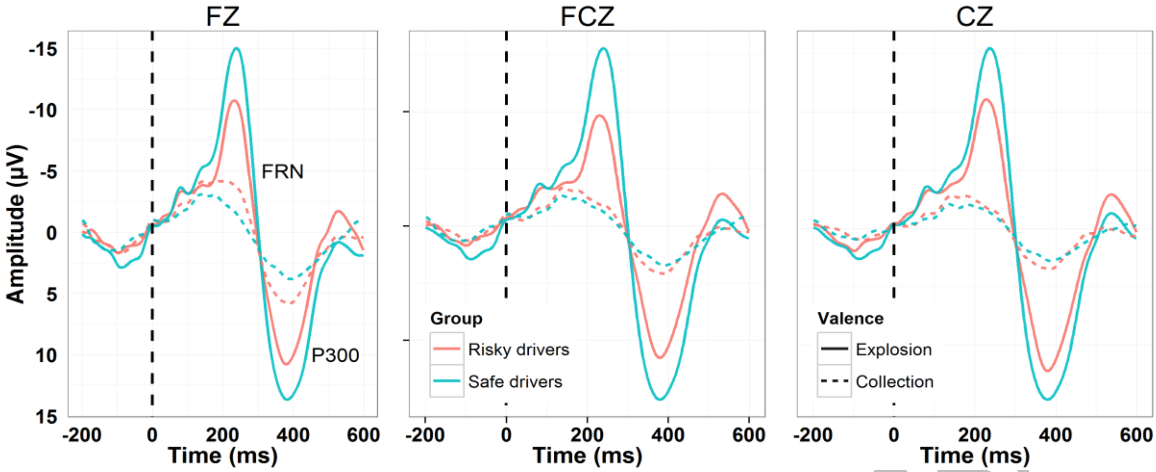

Figure 5 Grand-average ERP of BART for risky and safe drivers across feedbacks and electrodes

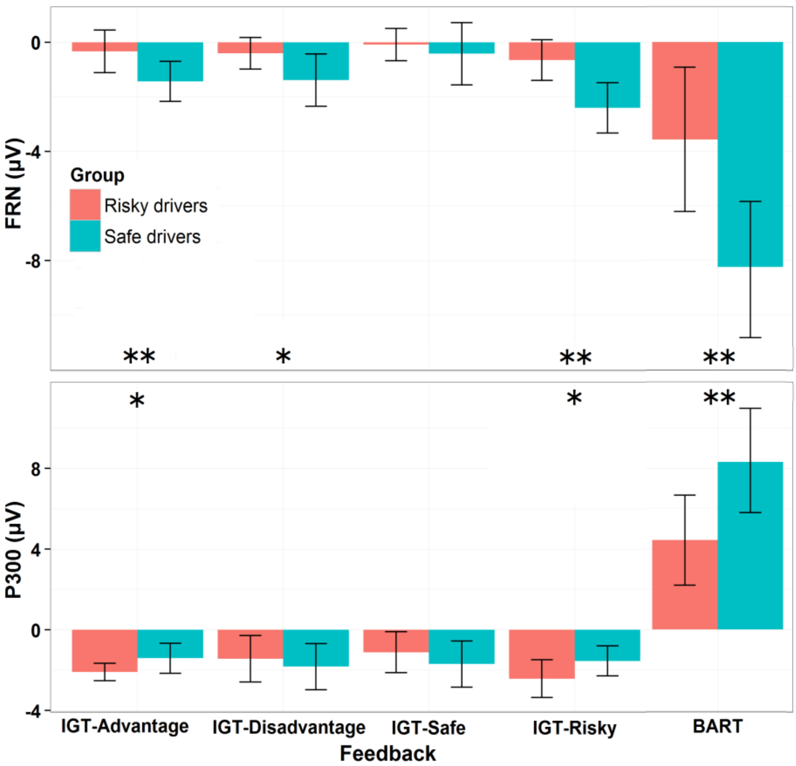

Figure 6 FRN and P300 loss-minus-gain amplitudes for risky and safe drivers. Error bars depicted standard deviations. Negative-going loss-minus-gain FRN indicated that the negative feedbacks evoked more pronounced error signals than positive feedbacks. Positive-going loss-minus-gain P300 indicated that the negative feedbacks evoked higher motivational attentions than positive feedbacks. Negative-going loss-minus-gain P300 indicated that the positive feedbacks evoked higher motivational attentions than negative feedbacks. Significances of between-group comparisons: $* p < .05$, $** p < .01$