Relationships between Driver Errors and Delay Discounting in a Simulated Driving Task

Paul Romanowich, Qian Chen & Shouhuai Xu

Perspectives on Behavior Science
An Official Journal of the Association for Behavior Analysis International

ISSN 2520-8969

Perspect Behav Sci
DOI 10.1007/s40614-020-00246-y

ONLINE FIRST

Springer

Perspectives on Behavior Science
https://doi.org/10.1007/s40614-020-00246-y

HEALTH, TECHNOLOGY & BEHAVIOR SCIENCE

Relationships between Driver Errors and Delay Discounting in a Simulated Driving Task

Paul Romanowich[1] · Qian Chen[2] · Shouhuai Xu[3]

Published online: 19 February 2020

Abstract
The majority of vehicle accidents are attributable to driver error, such as substance use, distractions, fatigue, speeding, and driving experience. Many of these driver errors are also associated with delay discounting, where individuals that excessively devalue a reward are more likely to use substances such as alcohol, cigarettes, and cocaine, and text-while-driving. The current study sought to examine a more direct association between delay discounting and driver error by providing 50 participants with a series of simulated driving tasks, along with measuring their delay discounting rates. A median-split for delay discounting rates showed that participants with high-delay discounting rates made significantly more total errors for simple driving tasks (e.g., braking and one-lane change) early during the simulation, relative to participants with low-delay discounting rates. On the other hand, high-delay discounting participants continued to make more total errors for a more complicated two-lane change driving task after multiple trials, relative to low-delay discounting participants. These results support the idea that delay discounting is a transdisease process that can significantly negatively affect a large range of health-related behaviors, including driver errors. Treatment implications for reducing driver errors are discussed.

Keywords Impulsivity · Security · Transportation · Vehicles

Delay discounting describes how quickly a reward, such as money, loses value as a function of time (Madden & Bickel, 2010). Individuals who prefer smaller, sooner

The authors would like to thank Gustavo Chavez and Jorge Castillo for computer programing, participant recruitment, and conducting the study with participants. Participant compensation was supported by a San Antonio Life Sciences Institute (SALSI) Cluster for Excellence grant to Drs. Xu and Chen.

✉ Paul Romanowich
romanowich@gonzaga.edu

1 Department of Psychology, Gonzaga University, 502 East Boone, Spokane, WA 99258, USA

2 Electrical and Computer Engineering, University of Texas at San Antonio, San Antonio, TX, USA

3 Department of Computer Science, University of Texas at San Antonio, San Antonio, TX, USA

rewards to larger, delayed rewards discount value more steeply than individuals who prefer larger, delayed rewards. Thus, delay discounting is a measure defined by how steeply value decreases as a function of increasing delays.

Delay discounting is significantly associated with several addictive behaviors, such as alcohol, cigarette, and cocaine use (MacKillop et al., 2011), where individuals using these substances discount rewards more steeply than former and/or nonusing individuals do. Researchers have begun describing steep discounting as a transdisease process, given the ubiquity of this association between substance use, other health-related problems (e.g., overeating, gambling) and steep discounting rates (Bickel, Jarmolowicz, Mueller, Koffarnus, & Gatchalian, 2012). A transdisease process affects a wide range of seemingly unrelated problem behaviors. Researchers have suggested that discounting rate may be such a process that affects a large range of problem behaviors (Bickel & Mueller, 2009). However, few of the problem behaviors associated with this transdisease process have been researched in relation to how delay discounting can affect technology use, and ultimately an individual's health. This article describes one part of a larger cross-disciplinary research collaboration focusing on ways to improve driver and vehicle safety by predicting who is more likely to make driver errors, and developing new ways to behaviorally authenticate drivers.

One recent research area demonstrating how technology use can relate to discounting rates and health involves texting while driving (TWD; Hayashi, Fessler, Friedel, Foreman, & Wirth, 2018). The National Highway Traffic Safety Administration (NHTSA) estimates that more than 481,000 individuals driving passenger vehicles were using handheld cell phones in the United States at any given time during 2016 (Pickrell & Li, 2017). The latest available statistics also show that between 6% and 16% of vehicle accidents in the United States were attributable to drivers engaged in texting (National Safety Council [NSC], 2015). However, this is likely an underestimate because not all states have data entry fields to capture texting on vehicle accident reports (NSC, 2017). In two separate studies, these researchers demonstrated that increased TWD was significantly positively associated with steeper discounting rates for hypothetical monetary rewards (Hayashi, Russo, & Wirth, 2015), and the opportunity to reply to a text message (Hayashi, Miller, Foreman, & Wirth, 2016). Although Hayashi et al. (2016) were not able to replicate the TWD association with steeper hypothetical monetary discounting rates, further studies have shown a significant relationships between TWD frequencies and hypothetical delays to a destination, and hypothetical probabilities for a motor vehicle crash (Hayashi et al., 2018). That is, individuals more frequently engaging in TWD were less likely to wait to send a text message as the delay to destination increased and the probability of a crash decreased, relative to those individuals not frequently engaging in TWD. Thus, the commodity being discounted (hypothetical money vs. driving outcomes) may affect the strength and/or significance for this association.

Although research showing a significant associations between TWD and discounting is consistent with the association between addiction and discounting rates, a larger issue about overall motor vehicle use and discounting remains largely unexplored. As previously noted, TWD only represents a portion of distracted driving or driver errors leading to accidents (NSC, 2015). In addition, the previous studies exclusively measured TWD through self-report data. More objective behavior-based data for both TWD and overall vehicle use are still needed to fully test the limits for these associations between these risky driving behaviors and delay discounting rates.

From 2005 to 2007 the NHTSA estimated that 94% of vehicle accidents were attributable to driver error (Singh, 2015). These driver errors encompass behaviors and states such as alcohol and illicit drug use, driver distractions (e.g., TWD), fatigue, excessive speed, and driving experience. If delay discounting is indeed a transdisease process, then not only TWD, but the majority of driver errors should be associated with steeper discounting rates. As previously mentioned, there is a robust literature detailing the association between drug use and discounting rates (MacKillop et al., 2011). However, to test the association between driver error and discounting rates requires either monitoring driving behavior in vivo, or conducting a driving simulation. The current study focused on the latter option, whereby individuals would experience a simulated driving course although being required to operate the steering wheel, brake, and accelerator in response to stimuli on the screen. The previous literature demonstrates a significant positive association between licit and illicit drug use, TWD and steeper discounting rates, where individuals using a variety of drugs discount monetary rewards more steeply (MacKillop et al., 2011), and individuals engaging in TWD more frequently discount time to destination and crash probabilities more steeply (Hayashi et al., 2018). These behaviors are also considered driver errors leading to vehicle accidents (Singh, 2015). Therefore, we hypothesized that participants whose choices on a delay discounting task indicated steeper discounting rates would also produce more errors during a simulated driving task.

Method

Participants

Fifty students at a large university in the southwest were recruited to complete a demographic questionnaire, a delay discounting measure, and a series of simulated driving tasks. To be eligible to enroll in the study, participants were required to be at least 17 years old, fluent in English, and have a valid driver's license. All participants were compensated with $10 immediately after completing these tasks. The study was approved by the local institutional review board (IRB) before data collection, and all participants were informed about their rights before informed consent was obtained.

Measures

Demographics Participants first answered demographic questions about their age, gender, ethnicity, income, and smoking, drinking, and marijuana use status. In addition, participants were asked open ended questions about what age they first obtained a driver's license and how many tickets they had previously received for moving violations (e.g., speeding). They were also asked whether they ever engaged in TWD, and their perception about how dangerous TWD was on a 101-point visual analog scale (VAS) slider. This VAS had anchors of 0 = not dangerous to 100 = extremely dangerous, and was demarcated by 10-point intervals. The slider was always set at 50 before participants responded.

Delay discounting Participants next completed a brief delay discounting for monetary gains questionnaire. Participants completed a list of 27 questions developed by Kirby, Petry, and Bickel (1999) that asked them to make choices between smaller, immediate rewards or larger, delayed rewards. For example, participants were asked to choose between either receiving $25 right now or $60 in 14 days. Previous delay discounting research has also shown that people discount real and hypothetical rewards at similar rates and hypothetical rewards are a valid proxy for real rewards (Johnson & Bickel, 2002; Madden, Begotka, Raiff, & Kastern, 2003). Discounting rate was based on the hyperbolic delay discounting equation:

$$V = \frac{A}{(1 + kD)}$$

where V is the subjective value of the delayed reward, A is the amount of the delayed reward, D is the delay to reward receipt. and k is a free parameter that indicates delay sensitivity (i.e., discounting rate). That is, participants with larger k-values are more likely to choose the smaller immediate rewards, relative to the larger delayed rewards.

Simulated driving task Participants completed three identical driving simulations operated on an OpenDS 3.5 driving simulator. Participants sat in a chair in front of a PC monitor running the OpenDS software, and a Logitech G29 driving force racing wheel and pedal that allowed participants to steer right and left, accelerate, and brake. The simulated driving task consisted of a 1.1 km straight 5-lane course where participants were instructed to operate the steering wheel, brake, and accelerator in response to two discriminative stimuli (S^D's) appearing on 20 gantries spaced 50 m apart. The S^D's were a red "X" that signaled for participant to decrease the vehicle speed to 20 km/h from 60 km/h, and a green arrow above the lane that signaled for participant to steer into the lane (either left or right) underneath the green arrow (see Fig. 1). After passing through each gantry, participants were asked to either steer the vehicle back to the center lane (if the previous gantry contained a green arrow), or accelerate back to 60 km/h (if the previous gantry contained a red X), which was the maximum speed available. An auditory cue was provided to signal that the reaction time had been recorded. Participants were given the following written instructions on the screen before beginning the first trial:

> Welcome to this driving simulator experiment. Please put on headphones for the entire duration of the experiment. In the following simulation you will be driving on a 5-lane road. Your task will be to drive in the center lane at full speed (60 km/h) and to stay in the lane as well as possible. Note: the car's speed is fixed between 20 km/h and 60 km/h. You will pass different sign gantries. Your task is to react as fast as possible to appearing signs. If the red sign (X) shows up, you will have to slow down as fast as possible to 20 km/h. DO NOT leave the center lane during your deceleration. If the green sign (arrow) shows up, you will have to steer your car to the indicated lane as fast as possible without slowing down. In a short distance after each sign gantry an acoustic signal will be played which

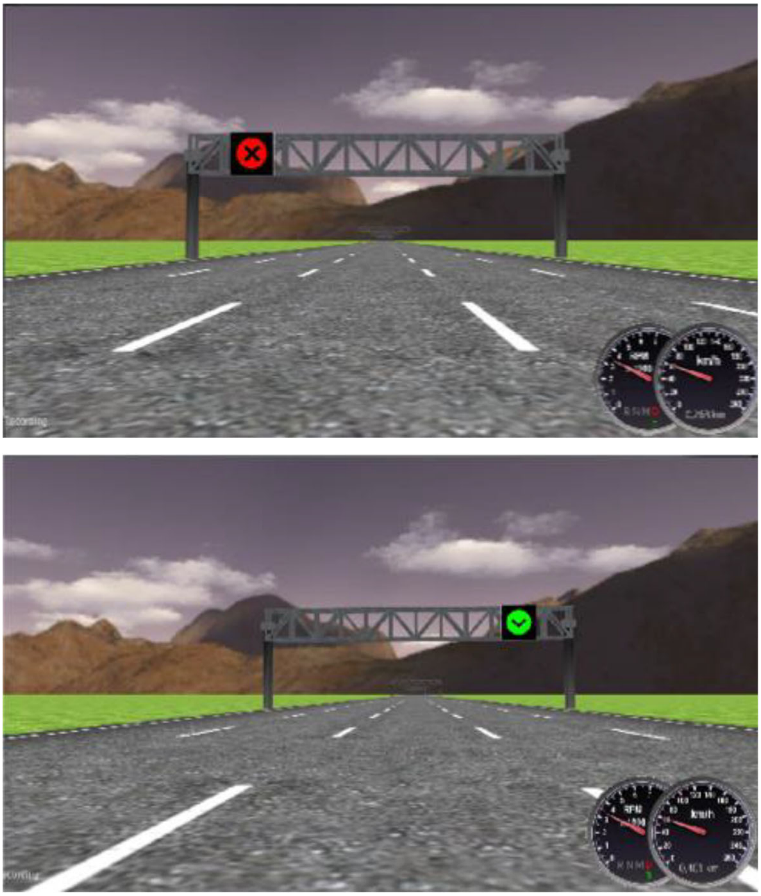

Fig. 1 The top panel shows a screenshot of a gantry with a red X. The red X served as a discriminative stimulus (S^D) signaling that the participants should slow down to 20 km/h. The bottom panel shows a screenshot of a gantry with a green arrow symbol. The green arrow was a S^D signaling which lane the participant should change to (from the center lane)

> indicates the end of the current reaction measurement. When you hear the signal please accelerate to full speed (60 km/h) and make sure to return to the center lane before the next sign. There will be three trials, each consisting of 20 gantries each. If you have questions, please contact the supervisor.

The first and last gantries contained no S^D. Therefore, 20 of the 22 total gantries contained 10 brake S^D's and 10 lane-change S^D's. Table 1 shows gantry presentation order. These tasks were selected to test participants' reaction times to different driving behaviors of varying complexity using the steering wheel, brake, and accelerator in a simplified driving environment. The first trial was designed for participants to practice the driving behaviors and habituate to the steering, braking, and accelerator functions. The second trial was designed to quantify reaction time differences and absolute number of errors between participants with varying delay discounting rates. The third trial changed the functionality of the steering wheel, brake, and accelerator to test

Table 1. Gantry presentation order

Gantry #	S^D	Behavior
1	Red X	Reduce Speed
2	Green O	2-Lanes Right
3	Red X	Reduce Speed
4	Red X	Reduce Speed
5	Red X	Reduce Speed
6	Green O	1-Lane Left
7	Red X	Reduce Speed
8	Green O	2-Lanes Left
9	Red X	Reduce Speed
10	Green O	2-Lanes Right
11	Green O	1-Lane Right
12	Green O	2-Lanes Left
13	Red X	Reduce Speed
14	Green O	2-Lanes Left
15	Red X	Reduce Speed
16	Green O	1-Lane Right
17	Red X	Reduce Speed
18	Green O	1-Lane Left
19	Red X	Reduce Speed
20	Green O	2-Lanes Right

participants' reactions to simulated "hacking" events. The third trial was not designed to test reaction time/errors, and is thus beyond the scope of the current article. In total, participants experienced up to 60 gantries containing a S^D across the three trials. Participants could complete each trial in approximately 5 min.

Analyses

For each participant, indifference points were calculated and plotted as a function of time. A free parameter k was used to indicate the steepness of the discounting curve that corresponded with the geometric midpoint of the ranges (Kaplan et al., 2016). Values ranged from 0.00016 to 0.25, with higher k-values indicating steeper delay discounting. In addition, consistency scores for participant's discounting data were calculated using the Kaplan et al. (2016) Excel spreadsheet. Consistency scores ranged between 89% and 100% (median = 96%).

Participants were separated into low- and high-discounting groups via a median split for obtained k-values. Obtained demographic measures were tested for differences between the low- and high-discounting groups using parametric statistics for normally distributed continuous measures, nonparametric statistics for nonnormally distributed continuous measures, and χ^2 tests for categorical measures.

For driving behavior, reaction time was defined as the time from when the S^D was presented on the gantry to when the appropriate driving behavior occurred. If the appropriate driving behavior did not occur the reaction time was coded as 10 s, as the average time to drive between each gantry was approximately 10 s. This 10 s measure was also coded as a driving error indicating that the participant did not complete the driving behavior before the next S^D was presented. Thus, driving errors were operationally defined as the omission of the behavior in response to the S^D during the entire 10-s gantry. This included inappropriate driving behaviors in response to the S^D (e.g., changing lanes when the S^D was a red X). Inappropriate driving behaviors followed by the appropriate driving behavior within the 10-s gantry did not count as an error, but necessarily increased reaction time. The OpenDS software collected driving behavior data (e.g., car position, steering wheel position, vehicle speed) every 0.05 s. Reaction time and driving error data were aggregated into three driving tasks: braking, one-lane changes, and two-lane changes, which contained 10, 4, and 6 gantries, respectively (see Table 1). Driving reaction time data for both trials were compared using a mixed ANOVA test, with the within-participant factor being the three types of driving tasks and the between-participant factor being low- or high-delay discounting. Driving error data were compared using separate χ^2 or Fisher's Exact tests.

Results

Table 2 shows the mean and percentage demographic information for the low- and high-discounting groups. The median *k*-value was 0.00972. *k*-values ranged from 0.00016 to 0.00971 for participants in low discounting group, and 0.00972 to 0.24837 for participants in the high-discounting group. None of the measured demographic variables were statistically different between the low- and high-delay discounting groups. On average, participants had first obtained a driver's license approximately 6 years before completing the simulated driving task. An equal number of participants ($n = 18$; 72%) in each group reported TWD. In addition, both groups perceived TWD to be dangerous (≥ 80 out of 100 on VAS).

Reaction time data for trial 1 (practice; top panel) and 2 (test; bottom panel) between groups and across the three driving tasks are shown in Fig. 2. Shapiro-Wilk normality tests showed that reaction time data were not normally distributed at $p < 0.05$ (W's < 0.88). Therefore, reaction time data were normalized using an inverse transformation (all W's > 0.95; except two-lane change on trial 1). For trial 1 a mixed ANOVA showed a significant within-participant main effect for driving task on reaction time, $F(2, 47) = 110.52$; $p < 0.001$; $\eta_p^2 = 0.70$. Post-hoc tests showed a significant reaction time difference between each of the driving tasks (all p's < 0.01). As shown in the top panel of Fig. 2, participants' reaction time was two-lane > one-lane > braking. There was not a significant between-participant main effect for delay discounting on reaction time, $F(1, 48) = 0.31$; $p = 0.58$; $\eta_p^2 = 0.01$, nor was there an interaction between driving task and delay discounting on reaction time, $F(1, 48) = 3.17$; $p = 0.08$; $\eta_p^2 = 0.6$ during trial 1.

Similar to trial 1, a mixed ANOVA for trial 2 data showed a significant within-participant main effect for driving task on reaction time, $F(2, 47) = 189.24$; $p < 0.001$; $\eta_p^2 = 0.80$. Post-hoc tests again showed a significant reaction time difference between each of the driving tasks (all p's < 0.01). As shown in the bottom panel of Fig. 2, participants' reaction time was again two-lane > one-lane > braking. There was not a

Table 2. Demographic data for participants in the low and high-delay discounting (DD) groups

	Low DD	High DD
n =	25	25
Mean Age (Stdev)	24.3 (8.2)	22.2 (4.2)
Mean Height (in; Stdev)	67.6 (4.1)	69.4 (8.8)
Mean Weight (lbs; Stdev)	175 (63.5)	160 (37)
% Female	36	32
Ethnicity		
% Hispanic	24	44
% White	44	20
% Black/Asian/Other	32	36
Income		
% $0 - 14,999	60	68
% $15,000-24,999	28	16
% $25,000+	12	16
Cigarette Use (%)	8	8
Alcohol Use (%)	60	52
Marijuana Use (%)	12	8
Mean Age Driving (Stdev)	17.2 (1.6)	17.7 (1.5)
Received Ticket (%)	32	40
Mean # (Stdev)	2.3 (2.4)	2.2 (1.0)
TWD (%)	72	72
Mean # (Stdev)	3.2 (8.0)	2.2 (1.3)
Perceived Danger (1-100)	80.0 (17.5)	87.4 (14.8)

significant between-participant main effect for delay discounting on reaction time, $F(1, 48) = 0.56$; $p = 0.46$; $\eta_p^2 = 0.01$, nor was there an interaction between driving task and delay discounting on reaction time, $F(1, 48) = 1.38$; $p = 0.25$; $\eta_p^2 = 0.3$ during trial 2.

Figure 3 shows the proportion of errors for each gantry between groups and across trials for all three driving tasks. During trial 1 high-delay discounting participants made almost twice as many total braking errors ($n = 33$), relative to low-delay discounting participants ($n = 17$). This difference was statistically significant, $\chi^2 = 5.69$, $p < 0.05$; $\Phi = 0.15$. However, as shown in Fig. 3a, this difference was largely a result of the first four braking gantries, after which there was no difference between groups during trial 1. The number of participants making at least one braking error in the high-delay discounting group was significantly larger ($n = 15$) than in the low-delay discounting group ($n = 6$), $\chi^2 = 6.65$, $p < 0.01$; $\Phi = 0.36$.

Likewise, for one-lane changes, high-delay discounting participants made more total errors ($n = 16$) than low-delay discounting participants ($n = 3$), $\chi^2 = 9.83$, $p < 0.01$; $\Phi = 0.31$. However, unlike braking gantries, Fig. 3b shows that the proportion of errors was higher for the high discounting group, relative to the low discounting group for all four gantries experienced during trial 1. The number of participants making at least one one-lane error in the high-delay discounting group was also significantly larger ($n = 10$) than in the low-delay discounting group ($n = 3$), $\chi^2 = 5.09$, $p < 0.05$; $\Phi = 0.32$.

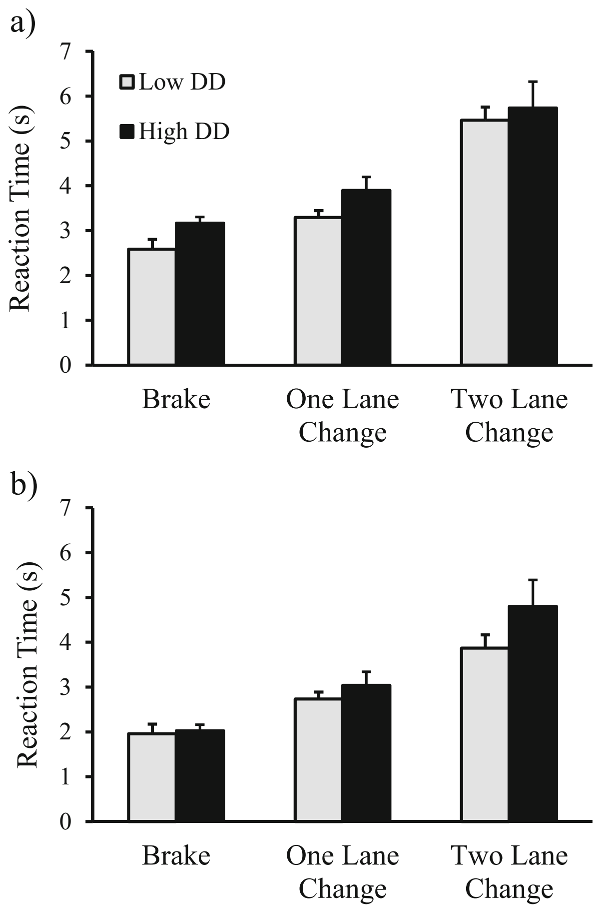

Fig. 2 The top graph shows mean reaction time (s) during trial 1 for aggregated driving tasks as a function of delay discounting (DD) group. The bottom graph shows mean reaction time (s) during trial 2 for aggregated driving tasks as a function of delay discounting (DD) group. In both graphs, grey bars represent low DD participants, whereas black bars represent high DD participants. In all cases, the vertical error bars represent standard error of the mean

Lastly, for two-lane changes, high-delay discounting participants made more total errors (n = 53) than low-delay discounting participants (n = 41). However, this difference was not statistically significant, $\chi^2 = 2.23$, $p = 0.14$. As shown in Fig. 3c, high-delay discounting participants began making a larger proportion of errors starting with gantry 3 on trial 1. The difference in the proportion of errors between groups remained relatively constant through gantries 4–6. The number of participants making at least one braking error in the high-delay discounting group (n = 15) was not significantly different from the low-delay discounting group (n = 17), $\chi^2 = 0.35$, $p =$ 0.55, because participants in both groups made a large number of two-lane driving errors.

During trial 2, Fig. 3 shows that the total amount of driver errors was reduced relative to trial 1. Fisher's Exact tests were used for comparing braking and one-lane change tasks. In both cases, there was no significant difference in errors made

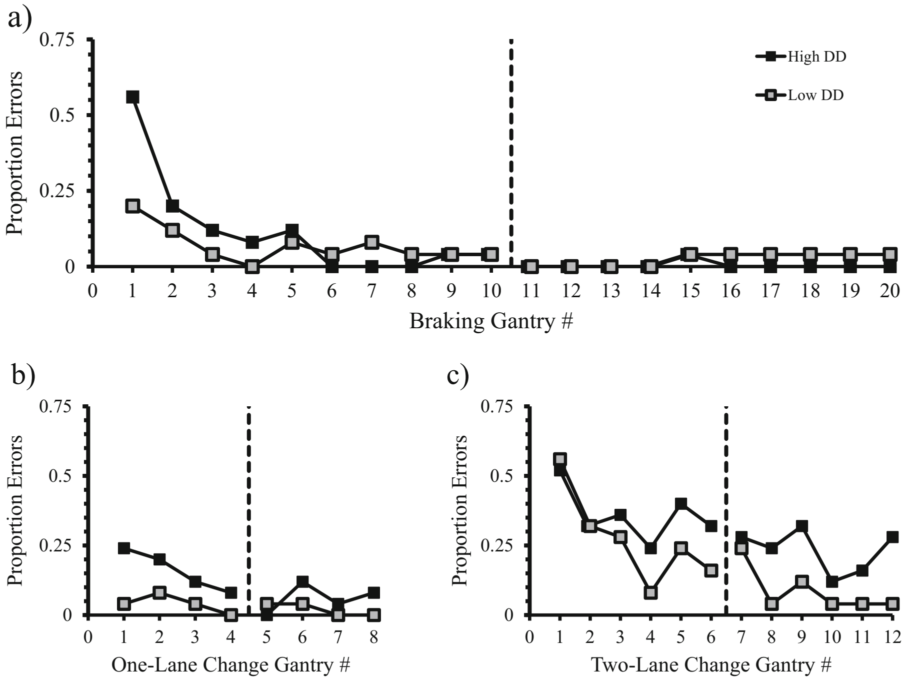

Fig. 3 The top graph (a) shows the proportion of driving errors made during braking gantries as a function of delay discounting (DD) groups across both driving trials. The bottom graphs (b & c) show the proportion of driving errors made during lane change gantries as a function of delay discounting (DD) group. In all graphs, grey-filled squares represent low DD participants, whereas black-filled squares represent high DD participants, and the vertical dashed line represents the time between trial 1 and 2. Gantry numbers do not correspond to the gantry presentation order shown in Table 1, but are each consecutive gantry for that specific task for trials 1 and 2

between delay-discounting groups for either the braking (p = 0.12), or one-lane change (p = 0.28) tasks. Fig. 3a-b shows this for gantries 11–20, and 5–8, respectively. Likewise, the number of participants making at least one braking or one-lane change error was not significantly different (all n's < 5). For two-lane change tasks, high-delay discounting participants made significantly more total errors (n = 35) than low-delay discounting participants (n = 13), $\chi^2 = 12.00$, $p < 0.001$; $\Phi = 0.28$. As shown in Fig. 3c (gantries 7–12) high-delay discounting participants continued to make more two-lane change errors than low-delay discounting participants during trial 2. Like trial 1, the number of participants making at least one two-lane change error was not different between the low (n = 7) and high (n = 10) delay discounting groups, $\chi^2 = 0.8$, $p < 0.37$.

Discussion

Fifty participants completed two simulated driving trials in which they were asked to either brake or change lanes in response to S^D's located on a series of gantries. Based on a median-split of participants' delay discounting rates, participants with higher delay discounting rates made significantly more errors during the braking and one-lane change tasks during the first trial than participants with lower delay discounting rates (Fig. 3a-b). During the second trial participants with higher delay discounting rates made more errors during the two-lane change task, relative to participants with lower delay discounting rates (Fig. 3c). The current results are consistent with previous studies on TWD and discounting showing that participants who engage in more frequent TWD also discount hypothetical delays to a destination, and hypothetical probabilities for a motor vehicle crash at higher rates (Hayashi et al., 2018). That is, higher delay discounting rates are correlated with less waiting to text as both time to a destination increases and the probability of a crash decreases. This study also extends previous research by using a driving simulation task to measure driving behavior errors, instead of self-reported driving-related behaviors (i.e., TWD frequency).

The relationship between delay discounting rate and driver error changed as a function of driving experience during the simulated driving task. High-delay discounting participants made significantly more errors during braking and one-lane change tasks early in trial 1, relative to low-delay discounting participants. However, by the end of trial 1 these group differences were largely eliminated for braking gantries, and at a low proportion for both groups during one-lane change gantries. However, group differences in two-lane change tasks *increased* from trial 1 to trial 2, with high-delay discounting participants making more two-lane change errors during trial 2, relative to low-delay discounting participants. The relative reaction time differences between tasks was consistent throughout both trials (see Fig. 2), with the two lane-change task taking significantly more time than the one-lane change and braking tasks. Combined with the changing error rates between delay discounting groups, this suggests that the two-lane change task was more difficult than both the one-lane change and braking tasks. In effect, high-delay discounting participants had a more difficult time learning to respond appropriately during the two-lane change task, even after multiple practice trials (see Fig. 3c). For example, during trial 1 (practice) one low-delay discounting participant and three high-delay discounting participants made errors on all six of the gantries signaling a two-lane change. That is, they made no correct responses during each 10-s interval. During trial 2 (test), none of the low-delay discounting participants made errors on all of the two-lane change trials, whereas four high-delay discounting participants made errors on all two-lane change trials. It is also notable that after experience with 12 two-lane change gantries, approximately 25% of high-delay discounting participants were still responding incorrectly. That is, those four participants who made errors on all two-lane change trials were not the only high-delay discounting participants still making errors.

There is still the question of why there were increased error rates for high-delay discounting participants. One hypothesis could be that the high-delay discounting participants were simply slower to respond to the S^D, which led to increased error rates via the operational definition for errors (i.e., the correct response was not made in the 10-s interval). However, when all errors (coded as 10 s) were removed from reaction-time calculations, reaction-time differences between low and high-delay discounting groups *decreased*. That is, errors coded as 10 s were increasing any measured differences in reaction time between groups (see Fig. 2). Another hypothesis could be that some other unmeasured process (e.g., attention) that was correlated with delay discounting was primarily causing increased error rates. Future studies should test this and other viable hypotheses. For example, attention could be measured by tracking eye movements during each trial.

Hayashi et al. (2015) originally reported a significant association between TWD frequency and delay discounting rates for hypothetical monetary rewards. However, they were unable to replicate this result in a subsequent study (Hayashi et al., 2016). The current findings are consistent with these latter results. Table 2 shows that there was no significant difference in self-reported TWD rates between high and low-delay discounting participants. Like Hayashi et al. (2015, 2016) all monetary rewards were hypothetical. Subsequent studies by Hayashi et al. (2018) showed significant associations between TWD frequencies and hypothetical delays to a destination, and hypothetical probabilities for a motor vehicle crash. Previous addiction studies have also found differential relationships between commodities and discounting rate (Bickel et al., 2011). In addition, cross-commodity delay discounting (e.g., small amount of money now, versus a larger amount of a preferred drug later) has in some cases been a better predictor of substance use patterns than the same commodity (e.g., small amount of drug now, versus a larger amount of drug later; Moody, Tegge, & Bickel, 2017). Like the study by Hayashi et al. (2016, 2018), future driver error research should begin to look at discounting rates for commodities that are more closely associated with driver errors. These behaviors may be the same ones causing the majority of vehicle accidents: alcohol and illicit drug use, TWD (e.g., hypothetical delays to a destination, and hypothetical probabilities for a motor vehicle crash), and excessive speed (Singh, 2015). Of course, this is an empirical question. Discovering these differential associations between driving errors and discounting rates will help target more effective interventions.

Conceiving of steep delay discounting as a transdisease process has led to numerous treatment efforts focused on decreasing these excessive discounting rates (e.g., Koffarnus, Jarmolowicz, Mueller, & Bickel, 2013). That is, instead of viewing delay discounting rates simply as a marker for dysfunctional behavior, these discounting rates are themselves the target for treatment. For example, addiction treatments have begun examining how mindfulness and distraction can profitably be used to decrease choices for the smaller sooner rewards, and increase choices for the larger later rewards (for review, see Ashe, Newman, & Wilson, 2015). Another procedure, episodic future thinking, has also been shown to reduce delay discounting rates (Daniel, Stanton, & Epstein, 2013a, 2013b). Although these treatment techniques have not been used for decreasing TWD or driver errors, there is evidence that lower mindfulness levels predict higher TWD in young-adult drivers (Feldman, Greeson, Renna, & Robbins-Monteith, 2011). The current results are consistent with previous associations with problem behavior, such as drug use and delay discounting (MacKillop et al., 2011). Thus, future research is needed to determine whether techniques used to decrease delay discounting rates during addiction treatment (Ashe et al., 2015) and for obese individuals (Daniel et al., 2013a) are also useful for decreasing excessive discounting in drivers, and more important, decreasing TWD and driver errors.

A transdisease process for delay discounting also implies high comorbidity with other problem behaviors. However, from the current data there were no significant group differences in other problem behaviors typically associated with high discounting rates, such as drug use (see Table 1; MacKillop et al., 2011). This may be a function of the student convenience sample used for this study, or it may suggest a different association between driving errors and delay discounting. Determining this association also has implications for different potential treatments, as described above. If there truly is no comorbidity with other problem behaviors typically associated with higher delay discounting rates, the treatments that have shown efficacy for reducing discounting rates and concurrent problem behaviors (e.g., contingency management; Yi et al., 2008) may be less efficacious for targeting discounting rates and driving errors. Future research will need to test for associations between delay discounting and driver errors in more heterogeneous populations.

There are both advantages and limitations to using simulated driving technology to measure driving behavior. The biggest advantage for simulated technology is participant safety. IRB approval is unlikely for experiments where participants may be harmed. This necessarily limits experiments to well-controlled environments high in internal validity, but lower in external validity. Of course, high-internal and low-external validity is not unique to the current study and can be found throughout the discounting literature, including research on TWD where no actual texting occurs (Hayashi et al., 2018). However, low external validity is still a limitation that should be addressed in future studies. Given more financial resources, more sophisticated driver simulations already exist (e.g., RDS-2000; https://www.faac.com/realtime-technologies) that can better model a natural driving environment. Similar to generalizing from a simulation to natural driving environments, another limitation is generalizing the current results to different participant samples. The current study used a convenience sample of university students. However, given the preliminary nature of this project, we believe the current participant sample is justifiable. Future studies should target drivers with more driving experience, especially those drivers who operate commercial vehicles (i.e., Class B & C driver licenses).

In sum, the current results demonstrate that individuals with higher delay discounting rates make more driving errors during a simulated driving task. Although high-delay discounting individuals were able to minimize errors on two of the tasks (i.e., braking and one-lane change) across two trials, these early errors coupled with significantly more two-lane changes errors during trial 2 increases their risk of being involved in a vehicle accident (Singh, 2015). Increases in vehicle accidents directly affects their health along with those individuals around them. Future goals for this cross-disciplinary research collaboration include finding ways to reduce driver errors through mindfulness, episodic future thinking, behavioral skills training and computer-assisted driver authentication.

Acknowledgements Texas National Security Network Excellence Fund (2018-2019) to Dr. Nicole Beebe with Dr. Chen serving as senior personnel.

References

Ashe, M. L., Newman, M. G., & Wilson, S. J. (2015). Delay discounting and the use of mindful attention versus distraction in the treatment of drug addiction: a conceptual review. *Journal of the Experimental Analysis of Behavior, 103*(1), 234–248. https://doi.org/10.1002/jeab.122.

Bickel, W. K., Jarmolowicz, D. P., Mueller, E. T., Koffarnus, M. N., & Gatchalian, K. M. (2012). Excessive discounting of delayed reinforcers as a trans-disease process contributing to addiction and other disease-related vulnerabilities: emerging evidence. *Pharmacology & Therapeutics, 134*, 287–297.

Bickel, W. K., Landes, R. D., Christensen, D. R., Jackson, L., Jones, B. A., Kurth-Nelson, Z., et al. (2011). Single- and cross-commodity discounting among cocaine addicts: The commodity and its temporal location determine discounting rate. *Psychopharmacology, 217*(2), 177–187. https://doi.org/10.1007/s00213-011-2272-x.

Bickel, W. K., & Mueller, E. T. (2009). Toward the study of trans-disease processes: A novel approach with special reference to the study of co-morbidity. *Journal of Dual Diagnosis, 5*(2), 131–138.

Daniel, T. O., Stanton, C. M., & Epstein, L. H. (2013a). The future is now: Comparing the effects of episodic future thinking on impulsivity in lean and obese individuals. *Appetite, 71*, 120–125.

Daniel, T. O., Stanton, C. M., & Epstein, L. H. (2013b). The future is now: Reducing impulsivity and energy intake using episodic future thinking. *Psychological Science, 24*, 2339–2342.

Feldman, G., Greeson, J., Renna, M., & Robbins-Monteith, K. (2011). Mindfulness predicts less texting while driving among young adults: examining attention- and emotion-regulation motives as potential mediators. *Personality & Individual Differences, 51*(7), 856–861. https://doi.org/10.1016/j.paid.2011.07.020.

Hayashi, Y., Fessler, H. J., Friedel, J. E., Foreman, A. M., & Wirth, O. (2018). The roles of delay and probability discounting in texting while driving: towards the development of a translational scientific program. *Journal of the Experimental Analysis of Behavior, 110*(2), 229–242.

Hayashi, Y., Miller, K., Foreman, A. M., & Wirth, O. (2016). A behavioral economic analysis of texting while driving: Delay discounting processes. *Accident Analysis & Prevention, 97*, 132–140.

Hayashi, Y., Russo, C. T., & Wirth, O. (2015). Texting while driving as impulsive choice: A behavioral economic analysis. *Accident Analysis & Prevention, 83*, 182–189.

Johnson, M. W., & Bickel, W. K. (2002). Within-subject comparison of real and hypothetical money rewards in delay discounting. *Journal of the Experimental Analysis of Behavior, 77*(2), 129–146.

Kaplan, B. A., Amlung, M., Reed, D. D., Jarmolowicz, D. P., McKerchar, T. L., & Lemley, S. M. (2016). Automating scoring of delay discounting for the 21- and 27-item monetary choice questionnaires. *The Behavior Analyst, 39*(2), 293–304.

Kirby, K. N., Petry, N. M., & Bickel, W. K. (1999). Heroin addicts have higher discount rates for delayed rewards than non-drug-using controls. *Journal of Experimental Psychology: General, 128*(1), 78–87.

Koffarnus, M. N., Jarmolowicz, D. P., Mueller, E. T., & Bickel, W. K. (2013). Changing delay discounting in the light of the competing neurobehavioral decisions systems theory: A review. *Journal of the Experimental Analysis of Behavior, 99*(1), 32–57.

MacKillop, J., Amlung, M. T., Few, L. R., Ray, L. A., Sweet, L. H., & Munafò, M. R. (2011). Delayed reward discounting and addictive behavior: A meta-analysis. *Psychopharmacology, 216*(3), 305–321.

Madden, G. J., Begotka, A. M., Raiff, B. R., & Kastern, L. L. (2003). Delay discounting of real and hypothetical rewards. *Experimental & Clinical Psychopharmacology, 11*(2), 139–145.

Madden, G. J., & Bickel, W. K. (2010). *Impulsivity: The behavioral and neurological science of discounting*. Washington, DC: American Psychological Association.

Moody, L. N., Tegge, A. N., & Bickel, W. K. (2017). Cross-commodity delay discounting of alcohol and money in alcohol users. *The Psychological Record, 67*(2), 285–292. https://doi.org/10.1007/s40732-017-0245-0.

National Safety Council. (2015). *Annual estimate of cell phone crashes*, *2013* Retrieved from http://www.nsc.org/DistractedDrivingDocuments/CPK/Attributable-Risk-Summary.pdf.

National Safety Council. (2017). *Undercounted is underinvested: How incomplete crash reports impact efforts to save lives*. Retrieved from https://www.nsc.org/Portals/0/Documents/DistractedDrivingDocuments/Crash%20Report/Undercounted-is-Underinvested.pdf

Pickrell, T. M., & Li, H. (2017). *Driver electronic device use in 2016* (Traffic Safety Facts Research Note. Report No. DOT HS 812 426). Washington, DC: National Highway Traffic Safety Administration.

Singh, S. (2015). *Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey*. (Traffic Safety Facts Crash and Stats. Report No. DOT HS 812 115). Washington, DC: National Highway Traffic Safety Administration. Retrieved from https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812115

Yi, R., Johnson, M. W., Giordano, L. A., Landes, R. D., Badger, G. J., & Bickel, W. K. (2008). The effects of reduced cigarette smoking on discounting future rewards: An initial evaluation. *The Psychological Record, 58*(2), 163–174.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.