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Traumatic Brain Injury Hinders Learning of Road Hazard Awareness by Repeated Exposure to Video-Based Hazards

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Objective: To better understand hazard awareness abilities among traumatic brain injury (TBI) survivors of which little is currently known. TBI survivors express degradation in driving abilities, particularly the proactive strategy in which indicators of potentially hazardous situations are sought and identified. The current study examined differences in hazard awareness learning between TBI survivors and noninjured control individuals matched for age and driving experience. ***Method:*** Forty individuals equally divided among the 2 groups were assessed by exposure to repetitive video-based hazard scenarios, which have been shown to improve hazard awareness in noninjured individuals. Differences in participants' eye movements and behavioral response while watching video clips of genuine traffic scenes were recorded. ***Results:*** Although survivors of TBI demonstrated relatively intact hazard awareness abilities under baseline conditions, they failed to learn from repetitive presentation of the same hazardous situation (i.e., they did not improve hazard detection) and thus failed to adjust their scanning and behavioral reaction (e.g., time to reaction, adapt of scanning behavior). Differences were more prominent for hidden hazards. Our results show impoverished anticipation abilities in driving simulation tasks performed in the subacute recovery phase after TBI and that differences in materialized hazards awareness are distinguishable between TBI survivors and noninjured drivers of similar age and driving experience. ***Conclusions:*** Our findings signal the need for further research to clarify the relationship between TBI and hazard awareness training that might be supportive of driving rehabilitation after TBI.

General Scientific Summary
The current study examined, via eye movements monitoring, differences in road hazard awareness between traumatic brain injury (TBI) survivors and noninjured control individuals matched for age and driving experience. Survivors of TBI failed to adjust their scanning and behavioral responses toward road hazards. Our results confirm that impoverished anticipation abilities underscore the ability of TBI survivors to drive safely.

Keywords: traumatic brain injury, driving, hazard awareness, eye movement, implicit learning

For adults recovering from moderate to severe traumatic brain injury (TBI), the return to driving a motor vehicle is an important step in resuming a normal lifestyle because the ability to drive plays a special role in the functional independence and well-being of most adults (Brenner, Homaifar, & Schultheis, 2008; Kreutzer et al., 2003; Novack et al., 2010; Rapport, Bryer, & Hanks, 2008). However, previous research has suggested that drivers who experience TBI tend to have more traffic violations (Formisano et al., 2005; Pietrapiana et al., 2005), drive slower (in a simulated environment; Cyr et al., 2009), and perhaps most important, have an increased risk of crash compared with noninjured people (e.g., Formisano et al., 2005; Haselkorn, Mueller, & Rivara, 1998; Lundqvist, Alinder, & Rönnberg, 2008; Schanke, Rike, Mølmen, & Østen, 2008; Schultheis, Matheis, Nead, & DeLuca, 2002). For example, Schanke and colleagues (2008) used a self-developed questionnaire to assess the driving behavior of 28 survivors of TBI. Results indicated that the self-reported accident rate of TBI survivors was more than twice as high as that of the general population (15.0 vs. 6.25 accidents per 1 million km driven). Cyr and col-

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leagues (2009) observed that in a simulated driving environment, TBI survivors who resumed driving were significantly more likely to crash in reaction to a surprising and challenging event compared with noninjured matched control individuals. A recently published literature review found no standard neuropsychological tests for predicting driving performance of TBI survivors (Palubiski & Crizzle, 2016). Nevertheless, a better characterization of the cognitive limitations of TBI survivors in the specific context of driving could be translated into an adapted retraining effort that could combine a cognitive training protocol within a driving context (Ross, Ponsford, Di Stefano, Charlton, & Spitz, 2016).

Hazard Awareness

Because TBI survivors often demonstrate difficulty in responding to novel or challenging events (Draper & Ponsford, 2008), they may have trouble executing a variety of driving abilities that are necessary for safe driving, including adequate and rapid processing of simultaneous inputs and anticipation of road hazards (Milleville-Pennel, Pothier, Hoc, & Mathé, 2010; Preece, Horswill, & Geffen, 2011; Van Zomeren, Brouwer, & Minderhoud, 1987). The ability to anticipate and be aware of hazardous situations is known as hazard awareness (HA) or hazard perception (e.g., Horswill & McKenna, 2004). It has received considerable attention over the years because it is among the few driving skills found to correlate with traffic crashes (Boufous, Ivers, Senserrick, & Stevenson, 2011; Congdon, 1999; Horswill, Anstey, Hatherly, & Wood, 2010; Horswill, Hill, & Wetton, 2015; McKenna & Horswill, 1999; Wells, Tong, Sexton, Grayson, & Jones, 2008). Horswill et al. (2015) found that drivers who failed an HA test had 25% more active crashes in the year preceding and the year following the test. Such findings support the HA test as being a measure of high ecological validity in assessing safe driving performance, leading to the integration of the HA test being into the United Kingdom licensing procedure in 2002 (Crundall, 2016).

Types of Hazards

Many factors are likely to influence and confound the response to a hazard situation. Among them are the visual cues that serve as an early indication of an upcoming hazard. For example, a child skating on a rollerblade along a crosswalk who is visible to the driver can be considered as a potential hazard that must be monitored because the child may burst into the road and become an actual hazard. Noticing and monitoring the child on the sidewalk will facilitate the driver's response should the child indeed burst into the road. A driver's ability to focus on areas and situations from which a hazard might develop and prioritize them enables that driver to detect road hazards earlier during the interval in which the hazards develop (Crundall, 2016; Pollatsek, Narayanaan, Pradhan, & Fisher, 2006). Considering this argument, hazards can be characterized based on the indicators that precede them. In the current study, we adopted an HA taxonomy that is based on prediction demands imposed on drivers (Borowsky & Oron-Gilad, 2013; Borowsky, Shinar, & Oron-Gilad, 2010). We relate to two factors in this taxonomy matrix: (a) whether the hazard has materialized or is yet unmaterialized (i.e., only a potential hazard) and (b) whether it is visible or hidden. A materialized hazard is defined as a hazard instigator (e.g., another road user) that is in a colliding course with the driver (e.g., a bicyclist on the sidewalk who suddenly bursts into the driver's path). This type of hazard calls for the driver's immediate response to prevent a crash. An unmaterialized hazard is defined as a hazard instigator that may or may not materialize, such as a bicyclist on the sidewalk who remains on the sidewalk throughout the scenario and who should therefore be monitored. The second factor is whether the hazard instigator is visible or obscured at the onset of the hazardous scenario. A hidden hazard is an instigator that is concealed by other road users or environmental factors, such as a pedestrian who is obscured by a parked, high-sided vehicle. A visible hazard is an instigator that is visible to the driver, such as a clearly visible pedestrian who is about to cross the road. These factors combined result in four types of hazards (i.e., hidden materialized, hidden unmaterialized, visible unmaterialized, and visible materialized). Anticipation demands are greater for hidden or unmaterialized hazard instigators (Crundall, 2016; Crundall et al., 2012).

A significant amount of literature used a driver's road visual scanning patterns to evaluate hazard anticipation (e.g., Borowsky et al., 2010; Crundall, 2016; Crundall et al., 2012; Crundall, Shenton, & Underwood, 2004; Underwood, 2007). Among plentiful eye-movement measures that represent visual scanning behavior (Hannula et al., 2010), fixation's characteristics are commonly used in the HA research. Eye position may be considered as a single fixation if changes in gaze position across samples are less than 1° of visual angle and, when combined, have a minimum duration of 100 ms (Hannula et al., 2010). An assessment of visual scanning ability can help in evaluating how cognitive difficulties influence the way in which visual information in the environment is used to refresh an internal mental model of the driving situation (Milleville-Pennel et al., 2010). For example, it is now well known that young, inexperienced drivers, who have an impoverished mental model of what is likely to happen on the road (Crundall, 2016; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), focus less on areas from where potential hazards are most likely to appear (Crundall et al., 2012; Pollatsek et al., 2006; Underwood, 2007).

To our knowledge, only one study has directly questioned how TBI is likely to affect HA skill (Preece et al., 2011). In that study, TBI survivors anticipated traffic hazards much more slowly than age-matched, noninjured control individuals did. Nevertheless, the researchers did not differentiate between hazards with different predictive demands, so the question of whether survivors of TBI will react differently to various kinds of hazards remains open. Because TBI contributes to executive function impairment (Kersel, Marsh, Havill, & Sleigh, 2001), that is, the ability to regulate and control behavior through metacognitive abilities such as inhibition and planning (Levin et al., 1996), and because prediction is an executive function (Gioia & Isquith, 2004), we hypothesized that the HA performance of TBI survivors will depend on the predictive demand of the hazardous situation. One way to test this hypothesis is to investigate whether TBI survivors will demonstrate preserved HA performance for hazards with low predictive demands, such as visible and materialized hazards, and impaired HA performance when the hazard has high predictive demands, such as hidden or unmaterialized hazards. If this indeed is the case, the findings would indicate that TBI indeed impairs anticipation abilities.

Because at least one study (Haider, Eberhardt, Kunde, & Rose, 2013) has shown that knowledge acquired during the first few experiences facilitates anticipation in further experiences of the same situation (Haider et al., 2013), another way to test the hypothesis is to examine whether survivors of TBI can learn to anticipate the future development of hazardous situations based on previous experiences. Accordingly, if prediction ability deficits lead to impaired HA in TBI survivors, one should expect that compared with noninjured drivers, survivors would demonstrate impaired anticipation of the upcoming hazard even though they had been previously exposed to the same hazardous scenario.

Improvement in anticipation skills may be assessed through repeated exposure to the same stimulus while the individual's response time is measured during each repetition. Facilitation of response time (RT) is typically observed when exposure to repetitive visual configurations is compared with exposure to nonrepetitive visual configurations (Goujon, Didierjean, & Thorpe, 2015; Li, Aivar, Kit, Tong, & Hayhoe, 2016; Schlagbauer, Müller, Zehetleitner, & Geyer, 2012; Zang, Zinchenko, Jia, Assumpção, & Li, 2018). Faster RT is interpreted as improved anticipation of the spatial location from which the next stimulus is expected to appear (Kahana-Levy, Shavitzky-Golkin, Borowsky, & Vakil, 2019a; Kahana-Levy, Shavitzky-Golkin, Borowsky, & Vakil, 2019b; Vakil, Bloch, & Cohen, 2017). Evidence of such a repetition effect develops in the face of even a very small number (two–four) of repetitive displays (Kahana-Levy et al., 2019a, 2019b; Schlagbauer et al., 2012; Zang et al., 2018).

To summarize, the present study aimed to compare differences in HA performance between TBI survivors and noninjured control individuals matched for age and driving experience. To the best of our knowledge, no study has yet examined the effects of anticipation demands and learning based on repetitive presentation of hazardous situations on the process of road scanning among of TBI survivors. We believe that examining these repetition effects can provide information on the quality of anticipation skills on the part of TBI survivors and its effects on their driving performance. Thus, the current study investigates the effects of different types of road hazards and a repetition-based learning procedure on the visual search strategies of TBI survivors while observing video clips of real-world hazardous situations.

Research Hypotheses

Leaning on the assumption that HA differences between TBI survivors and noninjured drivers can be measured in terms of different scanning performance and responses toward hazardous situations while watching video clips (e.g., Underwood et al., 2003), we hypothesized the following:

Hypothesis 1: At the initial presentation of hazardous scenarios, before the repetition-based learning procedure occurs, TBI survivors will demonstrate scanning and response patterns that are similar to those of noninjured control individuals matched for age and driving experience while watching visible and materialized hazardous situations and impaired awareness while watching hidden and unmaterialized hazards. Specifically, TBI survivors will fixate less often and more slowly on areas from which potential hazards might appear, which will demonstrate a wider spread of search while watching for hidden and unmaterialized hazardous situations (cf. Borowsky & Oron-Gilad, 2013; Borowsky et al., 2010; Underwood, 2007).

Hypothesis 2: Individuals in the control group will benefit more than TBI survivors will from repetitive exposure to the same hazardous scenarios, demonstrating a learning curve over repeated exposure to the same hazard.

Hypothesis 3: During the repetitive learning procedure an interaction effect will be found in which the pretraining differences in responses and scanning patterns between TBI survivors and noninjured drivers will be more prominent with respect to unmaterialized and hidden hazards and less so for visible materialized hazards. That is, the control group will demonstrate a better learning effect compared with TBI survivors for hidden unmaterialized hazards, whereas both groups will demonstrate learning effects with respect to visible materialized hazards.

Method

Participants

The ethics committees of the patient's rehabilitation center approved the experiment. A total of 40 individuals participated as paid volunteers. The experimental group, recruited at a Brain Rehabilitation Department, included 20 participants with subacute TBI who had been hospitalized for rehabilitation. Inclusion criteria were as follows:

1. The TBI injury was sustained at least three months before the study and classified as moderate-to-severe based on Glasgow Coma Scale (GCS) scores of 3−12. All participants were out of posttraumatic amnesia at time of the assessment.

2. Participants had a normal visual acuity of 6/9 or better and normal contrast sensitivity.

3. All participants had a driving experience of more than two years and received their driving license at least two years before the brain injury occurred. None of the participants held a valid driver's license at the time of the assessment because of the head injury.

Exclusion criteria included premorbid or current psychiatric illness, additional head injury, or other somatic or neurological illnesses that cause cognitive deficits, such as visual field loss, neglect, and dominant side hemiparesis, that might limit the participants' future driving possibilities. All TBI survivors had been injured at least three months earlier (M = 105.75 days, SD = 21.4) and experienced nonpenetrating moderate-to-severe TBI and had been hospitalized in a rehabilitation department for the entire study period. Participants with TBI included one woman and 19 men, ages 20−66 years (M = 42.52, SD = 14.13), with an average driving experience of 22.38 months (SD = 13.40). Injury details, medical information, GCS scores, and brain imaging findings of survivors of TBI were obtained from participants' medical records. Injury profiles of participants are presented in Table 1. The control group included 20 noninjured drivers who matched the TBI survivors in sex, age, and driving experience. Participants in the control group were ages 21−62 years (M = 41.35, SD = 13.10), with an average driving experience of 20.25 months (SD = 11.67).

Table 1
Characteristics of Study Participants With Traumatic Brain Injury

Participant	Sex	Age (years)	Driving experience (years)	Time since injury[a]	Cause of injury	GCS	Location of injury	Degree[b]
1	Male	38	21	3	MVA	12	DAI	Moderate
2	Male	20	2	3 (4)	MVA	3	SAH	Severe
3	Male	53	35	3 (2)	MVA	3	DAI	Severe
4	Male	63	43	3 (8)	Fall from a high spot	12	R temporal skull fractures, SAH	Moderate
5	Male	57	37	3	Fall from a high spot	12	L temporal SDH	Moderate
6	Female	46	10	3 (5)	MVA	4	R temporal ICH, s/p craniotomy	Severe
7	Male	44	27	3 (2)	MVA	3	SAH, base of skull fracture	Severe
8	Male	49	30	4 (10)	MVA	5	DAI	Severe
9	Male	58	35	3 (26)	Sport injury	12	R temporal SDH	Moderate
10	Male	51	33	4 (1)	MVA	5	DAI, R frontal fracture, s/p craniotomy	Severe
11	Male	44	25	2 (25)	Shooting	3	R temporal SAH, s/p craniotomy	Severe
12	Male	66	46	3 (24)	Explosion	3	R temporal fracture, s/p craniotomy	Severe
13	Male	58	35	5 (21)	MVA	12	L temporo-parietal fracture, SAH	Moderate
14	Male	43	25	3 (6)	Fall from a high spot	10	SAH, R temporo-frontal contusion	Moderate
15	Male	24	3	3 (8)	MVA	4	s/p L fronto-temporo-parietal, epidural, s/p craniotomy, no focal lesion	Severe
16	Male	40	15	15 (23)	MVA accident	7	Bilat, fronto-parietal	Moderate
17	Male	43	24	4 (6)	MVA	7	DAI, bilat temporal and R frontal	Severe
18	Male	20	2	3 (2)	MVA	3	L occipital	Severe
19	Male	21	4	4 (7)	MVA	10	DAI	Moderate
20	Male	34	14	3 (11)	Fall from a high spot	5	DAI, L frontal	Severe
M		42.52	22.38	3 (16)				
SD		14.13	13.93	21.40				

Note. GCS = Glasgow Coma Scale; MVA = motor vehicle accident; DAI = diffuse axonal injury; SAH = subarachnoid hemorrhage; L/R = left/right hemisphere; SDH = subdural hematoma; ICH = intracerebral hemorrhage; s/p = status post, after; Bilat = bilateral.
[a] Time since injury is months (and days). [b] As described on the patient's file.

Apparatus (Eye Trackers and Displays)

Eye movements were recorded using an SMI iView 250-Hz RED portable eye-tracking system (Version 2.5 SMI, Berlin, Germany) installed on a laptop computer (17-in. liquid crystal display, resolution 1,360 × 768 pixels). The recording device was installed beneath the screen. The sample rate of visual gaze was 60 Hz, with a nominal accuracy of 1° of visual angle. In addition to eye movements, participants' responses were initiated by pressing the space bar and recorded using E-PRIME 2.0 software (Psychology Software Tools, Inc., Pittsburgh, PA, USA).

Participants sat an average distance of 65 cm from the display. Fixation extraction was calculated based on three parameters: minimum fixation duration (100 ms), minimum dispersion considered a fixation (1 visual degree), and maximum consecutive sample loss (infinity). A computer located next to the participant was used by the experimenter to operate the eye-tracking software and to control the participant's computer. An external data cable was used to synchronize the stimuli (movie frame number and space bar presses) on the participant's computer with the eye-tracking sampling on the experimenter's computer.

Hazard Awareness Movies

Scenarios consisted of real-world driving filmed from a driver's perspective involving staged hazards of three main categories: visible materialized hazards, hidden materialized hazards, and hidden unmaterialized hazards. Movies of nonhazardous scenarios served as filler material (12 filler scenarios altogether) and were embedded among the target movies. The repetitive learning phase included only three target movies for two reasons. First, we wanted to maintain the implicit nature of the repetitions, assuming that more repetitions might elicit a participant's awareness of the repetitive nature of the task. Second, increasing the number of target scenarios requires the addition of filler scenarios between repetitions, which is believed to reduce the potential effects of learning (Zang et al., 2018). Scenarios used were edited into short video clips (between 20 s and 40 s).

All movies, filmed in a typical Israeli landscape at a rate of 25 frames/s and a resolution of 720 × 576 pixels, were adopted from previous studies (Borowsky & Oron-Gilad, 2013; Borowsky et al., 2010). To control for stimuli order effect, we generated four different sequences of target movies and counterbalanced them among the participants. All scenarios used in the study are described in Table 2 and Figure 1.

Experimental Design

Both groups of individuals (survivors of TBI and controls) underwent the repetition-based learning procedure. Participants

Table 2
Description of Target Hazard Awareness Movies

Movie ID and name	Hazard type	Exposure duration (ms)	Description
M-04: Lead vehicle	Visible materialized	3,420	Participant follows a lead vehicle on a one-way residential street. When the lead vehicle approaches an obscured intersection, a third car bursts into the lead vehicle's path from the right. The lead vehicle stops suddenly, directly in front of the participant.
M-20: Parked truck	Hidden unmaterialized	6,520	A truck is parked on the right side of an urban road, a few meters before a zebra crossing at an intersection. The truck obscures a potential pedestrian (hidden hazard) who might burst into the road before the truck. No pedestrian is actually present in this scenario.
M-26: Parked bus	Hidden unmaterialized turned to visible materialized	4,640	A bus is parked on the right side of a one-way residential street. The bus obscures a pedestrian who may burst into the road in front of the driver. The hidden unmaterialized hazard (pedestrian) eventually darts from behind the car and becomes a visible materialized hazard.

Note. M-04 = Lead vehicle movie; M-20 = parked truck movie; M-26 = parked bus movie. ID numbers correlate to our movie database and have no other meaning. M = movie.

were asked to respond when first noticing the hazard (for hazard definition, see Haworth, Symmons, & Kowadlo, 2000, p. 3, and also Borowsky et al., 2010). Participants were also informed that pressing the button would not stop the movie and that they should respond to a hazard only once. Data concerning eye movement and the pressing of the space bar were recorded throughout the study. Analyses were conducted separately for each movie and for each dependent variable.

During the HA training procedure, where learning was expected to occur, each target HA movie was presented four times (Zang et al., 2018) such that during the study each participant was exposed to 12 HA scenarios (3 movies × 4 repetitions) and 12 different filler scenarios (3 × 4), which were embedded among the target scenarios. Two independent variables constituted a 2 × 3 mixed design. The between-subjects independent variable consisted of the experimental group. The within-subject independent variable consisted of four repetitions. The learning curve was evaluated according to the changes in measurement of eye movement and behavioral response (space bar presses) across the four repetitions.

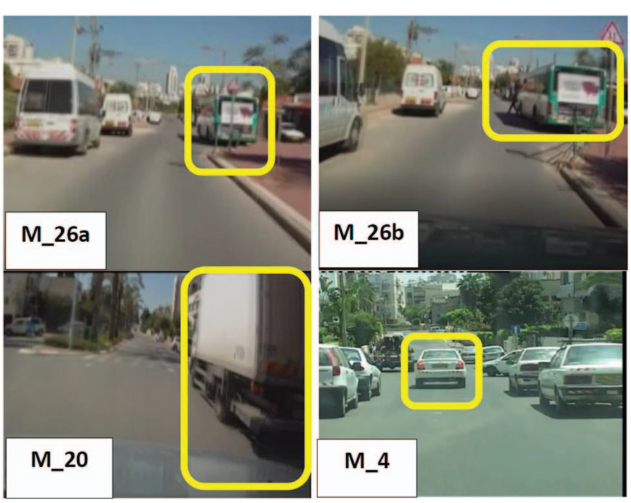

Figure 1. Hazards shown in hazard awareness movies. M-04 panel: lead vehicle in a visible materialized hazard scenario; M-20 panel: parked truck in a hidden unmaterialized hazard scenario; M-26a panel: parked bus in a hidden unmaterialized hazard scenario (frame at 2,000 ms from the initial appearance of the hazard); M-26b panel: parked bus in a visible materialized hazard scenario (frame at 3,000 ms from the initial appearance of the hazard). See the online article for the color version of this figure.

Procedure

All participants signed an informed consent and were asked about their driving history and demographic background. Participants were asked to sit approximately 65 cm in front of the computer monitor and read the experimental instructions, including the definition of the hazard. Participants donned the eye tracker, and after a short calibration process, they observed several practice movies to familiarize themselves with the experimental setup. Participants were instructed to observe each movie as if they were the driver in the scenario and to press the space bar each time they identified a hazard. When participants felt comfortable with the experimental task, they were asked to complete the HA training procedure. Participants were debriefed at the end of the experiment. The full procedure took about 1 hr without breaks.

Data Preparation of Eye Movements and Behavioral Responses

We first extracted eye movements and behavioral responses from sections of each movie in which a critical hazard or its preliminary indicators were observed until the moment when the participant's vehicle had passed the hazard and a response was no longer relevant. In preparing eye movement data, we defined areas of interest (AOIs) for each hazard across sections. AOIs were defined as areas from where the hazard instigator could have appeared for hidden hazards (e.g., the front edge of a truck obscuring a crosswalk) and the area surrounding the hazard instigator (e.g., a pedestrian) when a hazard was visible. As the view of the road progressed, AOIs were automatically adjusted. Calculations were based on the fixations that fell in each predefined AOI per repetition and participant.

Behavioral dependent variables. Following data preparation, two dependent variables were defined for behavioral data.

The main dependent variable was response probability; that is, the participants' ability to identify the hazard or its preliminary indicators correctly based on their behavioral response. A score of 1 was awarded to participants when they pressed the response button during the allotted time window of the hazard situation, whereas a score of 0 was assigned when participants did not press the response button during the hazard presentation or pressed it before or after the hazard event. This binary variable was calculated for each participant for every section of each hazard. The second variable, normalized response time (NRT), was calculated for only the correctly identified responses. When participants did not respond to a hazard during the allotted time window, the NRT score was treated as a missing value. *NRT* was defined as the time interval (in milliseconds) between the beginning of the hazardous event and the first response associated with the hazard divided by the total duration of the hazardous event. To analyze this variable, using analysis of variance we applied a natural logarithmic transformation on NRT. For example, if a certain hazardous event began at 12,000 ms, the total duration of its time interval was 9,000 ms, and the participants made their first fixation inside the hazard time frame at 15,000 ms, then the computed NRT would yield (15,000–12,000)/9,000 = .33, or −1.10 on a logarithmic scale.

Eye movements dependent variables. Three dependent variables were defined for eye movement data. The first was the normalized number of fixations. For each participant, we computed the total number of fixations. These were computed separately for fixations within or without the AOIs. We then normalized the number of fixations that participants made within the AOIs by dividing it by the overall number of fixations during the hazardous events (both inside and outside the relevant AOIs). For example, if a participant exhibited 20 overall fixations throughout the hazardous event, five of which were within an AOI, then the normalized number of fixations would yield 5/20 = .25, suggesting that 25% of the participant's fixations were directed toward AOIs. The other two variables were vertical and horizontal spread of search. These variables represent a participant's visual spread of search along the vertical and horizontal axes, respectively. They were computed separately for *x* and *y* coordinates as the standard deviation of fixation centers along each axis.

Results

Statistical Analyses

All main effects and second-order interactions of the fixed effects were included in the model. SPSS Version 22.0 software was used. Participants were included as a random effect. The two-way alpha value was set at 5%. To assess whether any differences in the dependent variables were due to group, repetition, or hazard type, we evaluated fixed and random effects through the generalized linear mixed model (GLMM) framework. Within this framework, we used a binary logistic regression method to assess response probability with a logit link function and a random intercept, whereas for each of the variables—NRT, normalized number of fixations, and vertical and horizontal spread of search—we used a linear regression within the same GLMM framework. The final model was achieved via a backward elimination procedure starting from the full model. For significant fixed effects, a post hoc pairwise comparisons procedure was applied and corrected for multiple comparisons by using the Bonferroni correction procedure. Analyses were carried out for three types of hazards: a visible materialized hazard (Movie M-04), a hidden unmaterialized hazard (Movie M-20), and a hidden materialized hazard (Movie M-26).

Visible materialized hazard (Movie M-04). Both groups showed a stable, highly estimated response probability toward visible materialized hazards across all repetitions (see Table 3, rows 2–5). Both study groups demonstrated a significant decrease in NRT across repetitions, $F(3, 148) = 4.21$, $p < .01$ (see Table 3, row 6). A review of the final model of the normalized number of fixations within the AOI revealed a main effect for group at the first section of the hazard, $F(1, 50976) = 199.35$, $p < .01$, which indicated that the control group had twice as many fixations on the

Table 3
Significant Effects and Post Hoc Analyses Across Response-Related Dependent Variables in M-04

Effect	R1	R2	R3	R4	Post hoc repetitions
			Response probability		
Repetition	.89	.97	.94	.96	*ns*
Group					
TBI	.80	.97	.97	.94	
Control	.94	.97	.97	.97	
Post hoc	*ns*				
			Normalized response time		
Repetition	.64 (.02)	.62 (.02)	.57 (.02)	.56 (.02)	M1 > M3 ($p < .05$); M1 > M4 ($p < .01$); M2 > M4 ($p < .05$)
Group					
TBI	.67 (.03)	.64 (.03)	.58 (.03)	.57 (.03)	
Control	.61 (.03)	.60 (.03)	.56 (.03)	.54 (.03)	
Post hoc	*ns*				

Note. Data represent estimated means, with standard errors in parentheses, of the dependent measure on Repetitions (R) 1–4. TBI = traumatic brain injury; M-04 = Lead vehicle movie.

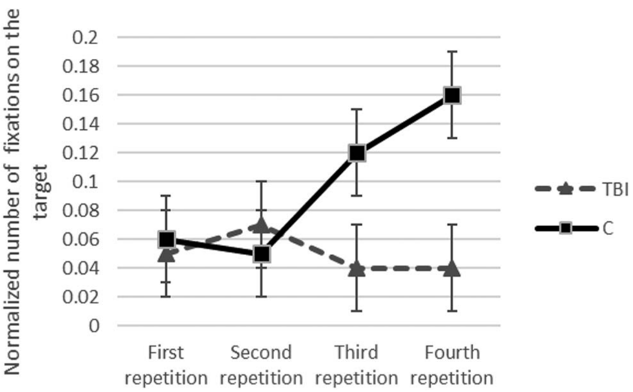

Figure 2. Normalized number of fixations on a visible materialized hazard of both TBI survivors and matched controls in repetition 1-4 (Movie M-04, lead vehicle movie). Error bars indicate standard error of the means. TBI = traumatic brain injury; C = control.

target compared with survivors of TBI (.10 compared with .05, respectively). In addition, the final model revealed a significant interaction between group and repetition, $F(3, 50976) = 2{,}476.90$, $p < .01$, suggesting a gradual decrease in the normalized number of fixations in the group of TBI survivors, as opposed to an incline in the normalized number of fixations in the control group. Those opposite tendencies developed into significant differences between groups at the third and the fourth repetitions (see Figure 2). No further significant differences were found in the dependent variable of supplemental eye movements.

Hidden unmaterialized hazard (Movie M-20). A gradual trend of increased probability to respond to the hidden unmaterialized hazard was observed in both groups. A Group × Repetition interaction revealed that whereas survivors of TBI had a stable, low-response probability (.15–.33; see Table 4, row 4), in the control group the response probability marginally increased (.29–.75; see Table 4, row 4), until it reached a significant difference compared with the group of TBI survivors (see Table 4, row 5). For NRT, interaction was found between group and repetition, $F(3, 63) = 2.88$, $p < .05$. In comparing NRT performance of the two groups, at the beginning of the training TBI survivors (only those who detected the hazard) demonstrated higher NRT compared with individuals in the control group (see Table 4, row 10). Nevertheless, this difference became smaller with later repetitions (except for the last repetition), because the NRT values of those in the TBI group who detected the hazard decreased along the first three repetitions (see Table 4, row 8), whereas the NRT of individuals in the control group remained stable. For eye movements, the interaction effect revealed that during the first section, when the hazard was presented, the control group exhibited more fixations on the target in the second and fourth repetitions compared with TBI survivors, $F(3, 114947) = 1{,}098.03$, $p < .01$ (see Figure 3A). Additionally, TBI survivors demonstrated a significant gradual incline in the horizontal spread of search, $F(3, 114947) = 464.12$, $p < .01$ (see Figure 3B).

Hidden materialized (Movie M-26). Individuals in both experimental groups exhibited a similar, relatively high, response probability toward hidden materialized hazards across repetitions. A marginally significant difference in NRT was found between groups (TBI survivors: $M = .8$, $SE = .03$; control group: $M = .72$, $SE = .03$), $F(1, 152) = 3.80$, $p = .05$. In addition, a trend toward a gradual decline along Repetitions 1−3 was also found, $F(3, 152) = 2.24$, $p = .08$ (see Table 5, rows 6–8). Additional pairwise comparisons between groups revealed that TBI survivors demonstrated a significantly higher NRT at the third, $F(1, 152) = 4.29$, $p < .05$ (see Table 5, row 9), and fourth, $F(1, 152) = 4.23$, $p < .05$ (see Table 5, row 10), repetitions. Additional separate pairwise comparisons between repetitions for each group revealed a gradual decline in NRT among individuals in the control group, $t(152) = 2.28$, $p < .05$ (see Table 5, row 11). A significant interaction between repetitions and groups was found for eye movements, $F(3, 57049) = 856.30$, $p < .01$, revealing that from Repetitions 2 to 4, during the first section of presentation of a hazard, survivors of TBI exhibited a gradual decline in the number of fixations toward the target, whereas individuals in the control group demonstrated the opposite tendency (see Figure 4).

Table 4
Significant Effects and Post Hoc Analyses Across Response Dependent Variables in M-20

Effect	R1	R2	R3	R4	Post hoc repetitions
			Response probability		
Repetition	.21	.45	.42	.55	M1 < M4 ($p = .06$.)
Group					
TBI	.15	.33	.20	.33	
Control	.29	.57	.66	.75	M1 < M4 ($p = .08$)
Post hoc			C > TBI ($p < .05$)		
			Normalized response time		
Repetition	.64 (.06)	.62 (.05)	.59 (.05)	.61 (.05)	
Post hoc		*ns*			
Group					
TBI	.77 (.09)	.68 (.08)	.57 (.08)	.70 (.08)	M1 > M3 ($p < .05$)
Control	.51 (.07)	.57 (.07)	.61 (.07)	.53 (.06)	
Post hoc	TBI > C ($p < .05$)				

Note. Data represent estimated means, with standard errors in parentheses, of the dependent measure on Repetitions (R) 1–4. TBI = traumatic brain injury; M-20 = parked truck movie.

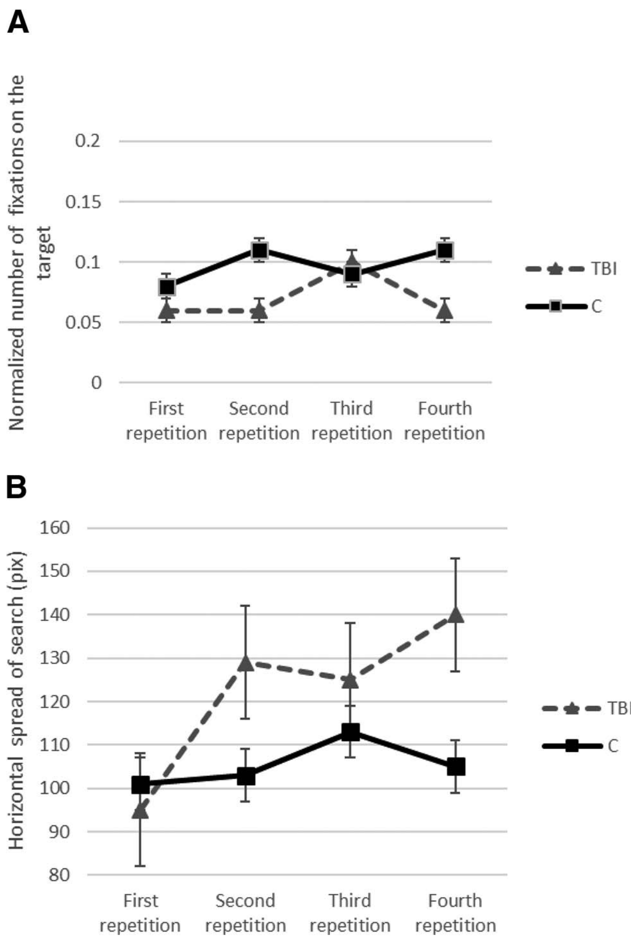

Figure 3. Panel A: Normalized number of fixations on a hidden unmaterialized hazard of both TBI survivors and matched controls (Movie M-20, Parked truck movie) at the first section in repetition 1-4. Panel B: Horizontal spread of search during a hidden unmaterialized hazard scenario of both TBI survivors and matched controls (Movie M-20) in repetition 1-4. Error bars indicate standard error of the means. TBI = traumatic brain injury; C = control.

Discussion

In this study, we compared the learning curves of driving traumatic brain injury (TBI) survivors and noninjured individuals matched for age and driving experience, with respect to the improvement of hazard awareness (HA) performance involving different prediction demands during repetitive video-based training. Our first hypothesis referred to the time frame during the first presentation of each hazard, that is, before the repetitive exposure to the hazard (known as the training procedure), where learning was expected to occur. TBI survivors, compared with individuals in the control group, were expected to demonstrate selective HA impairment influencing HA of hidden unmaterialized hazards, whereas HA of visible materialized hazards was expected to be preserved. To test this hypothesis, we examined the behavioral response and eye movements of both groups during the pretraining and training phases of exposure to short movie scenarios of hazardous driving situations. The results from the training phase supported our hypothesis only partially. First, no significant differences were found between the groups in recognizing materialized hazards (hidden or visible) during the first presentation of all the hazards, especially regarding oculomotor performance. The current findings contradict those of Preece and colleagues (2011), who found slower response time (RT) toward hazards among TBI survivors compared with matched controls. One possible explanation for the conflicting results reported by Preece and colleagues is that differences in RT between groups might reflect slower psycho-motor performance (e.g., eye scanning performance), a pattern that was previously described in other studies that investigated TBI survivors (e.g., Vakil & Lev-Ran Galon, 2014). A tendency toward a slower normalized response time (NRT) in the initial presentation of hazardous scenarios was also found in our group of TBI survivors compared with those in the control group. Thus, lack of scanning differences in the current study may imply that TBI survivors do not differ significantly from noninjured peers in their scanning strategies. Indeed, TBI survivors tend to have preserved well-practiced skills that were acquired before the injury, although those skills unfold more slowly (Korman et al., 2018; Nissley & Schmitter-Edgecombe, 2002; Schmitter-Edgecombe & Nissley, 2000). Because HA is a skill that improves with practice (Horswill et al., 2015), perhaps our TBI participants' preserved scanning performance reflects their relatively large amount of driving experience ($M = 22.93$ years, $SD = 13.93$). We believe that this tendency of slower NRT to visible materialized hazards among TBI survivors would have been more solid given greater statistical power. Effect size could be increased by the employment of a greater number of scenarios in future studies.

Our second hypothesis was that both groups would exhibit a similar learning effect after being repeatedly exposed to a visible materialized hazard but differential effects where hazard scenarios required higher anticipation demands. That is, facing an unmaterialized or hidden hazard, TBI survivors would benefit less from the repetitive learning procedure than their noninjured peers would. This hypothesis was also partially confirmed. The control group but not the TBI group exhibited an increase in the probability of responding to a hidden unmaterialized hazard and a decrease in NRT toward a hidden materialized hazard along the repetitive presentation of those hazards. Additionally, eye movement data confirmed that behavioral changes that occurred in the control group reflect better focus on the various hazards throughout repetitions, compared with that of the TBI survivors. Participants in the control group were able to gradually increase their focus on hidden and unmaterialized hazards, as reflected by a gradual increase in the number of fixations toward the hazards and a narrowed dispersion of fixations around the hazard. These results suggest that the control group allocated more attention to the hidden hazards across repetitions. In contrast, individuals in the TBI group focused less on the hidden hazards, as demonstrated by a broader horizontal spread of search in scenarios involving hidden unmaterialized hazards accompanied with a smaller number of fixations across repetitions on both materialized and unmaterialized hidden hazards. These results imply that TBI survivors exhibit impaired anticipation abilities, because they were not able to increase their focus on the hazardous situation regardless of the number of exposures to the hazardous scenario.

Altogether, our results suggest that mechanisms of active exploration based on predication through previous experience are

Table 5
Significant Effects and Post Hoc Analyses Across the Response Variables in M-26

Effect	R1	R2	R3	R4	Post hoc repetitions
			Response probability		
Repetition	.95	.95	.97	.94	*ns*
Group					
TBI	.94	.97	.94	.94	
Control	.94	.97	.97	.97	
Post hoc	*ns*				
			Normalized response time		
Repetition	.79 (.02)	.76 (.02)	.73 (.02)	.76 (.02)	M1 > M3 (p = .08)
Group					
TBI	.83 (.03)	.79 (.03)	.78 (.03)	.81 (.03)	
Control	.75 (.03)	.74 (.03)	.68 (.03)	.70 (.03)	M1 > M3 (p < .05)
Post hoc			TBI > C (p < .05)	TBI > C (p < .05)	

Note. Data represent estimated means, with standard errors in parentheses, of the dependent measure on Repetitions (R) 1–4. TBI = traumatic brain injury; M-26 = parked bus movie.

impaired in survivors of moderate-to-severe TBI. Indeed, a brain injury may impose specific constraints on action and thought schemata, both of which are constructs that allow new goal-directed behavior (Norman & Shallice, 1986; Shallice & Cipolotti, 2018). These constraints are manifested by reduced capacity to generate new responses that are based on conceptualization and anticipation processes (Duncan, 2010; Shallice & Cipolotti, 2018; Vakil, 2005; Vakil & Lev-Ran Galon, 2014). Of course, to further confirm the hypothesized connection between impaired HA and lower anticipation skills among TBI survivors, future studies should assess the anticipation abilities of the participants via neuropsychological assessment. In a small preliminary study, Milleville-Pennel et al. (2010) indeed showed that TBI survivors, who were impaired in their visual scanning pattern of a stimulator driving scene, also performed poorly in neuropsychological tests of anticipation and planning. Such results would allow one to suppose that people who suffer from a deficit in executive functions following brain injury may have some difficulties in searching for information that might be useful for planning a good trajectory and anticipating other events likely to occur on the road,

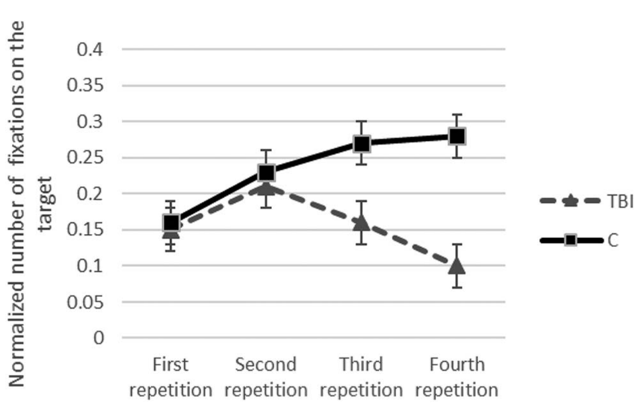

Figure 4. Normalized number of fixations on the hidden materialized hazard of both TBI survivors and matched controls in repetition 1-4 (Movie M-26), Parked bus movie. Error bars indicate standard error of the means. TBI = of traumatic brain injury; C = control.

as observed for inexperienced drivers (Borowsky et al., 2010; Kahana-Levy et al., 2019a).

Our finding that TBI survivors paid less attention to their anticipation of traffic hazards suggests that impaired HA could explain why drivers with severe TBI are overrepresented in traffic crashes compared with the general driving population (e.g., Formisano et al., 2005; Haselkorn et al., 1998; Lundqvist et al., 2008; Schanke et al., 2008; Schultheis et al., 2002). For an illustrative example, a 26% difference in RT between TRI survivors and controls in the hidden unmaterialized hazard scenario translates into a 1.5-s difference in response times between the groups. This is equivalent to a difference of 25 m in braking distance when driving at 60 km/h.

If the conclusion is that the ability of survivors of moderate-to-severe TBI to anticipate road hazards is impaired, then one must question whether common HA training methods used in training the general population can be used or adapted as a training intervention for individuals recovering from TBI. Although existing HA training methods for the general population have been proven to be successful (e.g., Horswill, Garth, Hill, & Watson, 2017; Kahana-Levy et al., 2019a, 2019b), the impaired repetitive learning ability among TBI survivors demonstrated in the current study might call into question the utility of using such materials in training TBI survivors. Further research is required to investigate whether HA training is suitable for drivers with special needs (e.g., see Bruce et al., 2017, for a study of individuals with attention-deficit/hyperactivity disorder) and could be adapted for use in training TBI survivors.

The ability to generalize results of the current study is limited by the low proportion of women (5%). This gender imbalance reflects the common notion that TBI, especially when severe, is typically associated with men (Bruns & Hauser, 2003; Peeters et al., 2015). Similarly, in this exploratory study, we recruited a convenience sample of TBI survivors in a subacute phase who were still hospitalized for rehabilitation. We acknowledge that TBI survivors can regain some of their cognitive function during a prolonged recovery period, up to 24 months post-TBI. Therefore, our results and conclusions should be taken as an exploratory examination of the efficiency of HA repetitive learning in a group of survivors of subacute TBI. Further investigation of the driving ability of individuals with moderate-to-severe TBI in later stages of rehabilitation may help answer whether implicit learning impairment is dependent on the time since injury. Indeed, giving our small sample size, investigation of the contribution of additional covariate variables was beyond the scope of this preliminary study. Nevertheless, further studies with a larger sample size should include various variables that might also effect TBI survivors' HA performance, such as age, TBI severity, and driving experience.

It is important to note that the TBI survivors detected fewer hidden unmaterialized traffic hazards than noninjured peers did, yet there was no evidence of variance in HA response probability with other types of hazards. It should also be noted that HA is primarily designed to be a response time and eye-tracking measure rather than a response probability test. The traffic scenes chosen for inclusion in the HA test were selected in part because most drivers would be likely to eventually respond to the hazard presented (Borowsky et al., 2010). In the current sample, this is illustrated by the highest possible hit rates characteristic of both groups, which would likely obscure any group differences. Therefore, caution should be taken when interpreting the response probability test. Nevertheless, enhanced statistical power might help reveal additional differences between TBI survivors and control participants and corroborate or refute trends established in the current study regarding the response probability measure, because interpretation that is based solely on NRT measures also has its limitations. For example, when a hazard had a lower anticipation demand (i.e., a visible materialized hazard), individuals in both study groups demonstrated a gradual decline in NRT. Standing alone, this data might have led us to conclude that TBI survivors benefited from the repetitive presentation of a visible materialized hazard scenario. Notwithstanding, TBI survivors did not demonstrate a similar learning curve in response probability and eye position measures. A possible explanation for this apparent contradiction between oculomotor and behavioral function (NRT) is that as opposed to all other measurements that were calculated for all participants, NRT was calculated only when a participant correctly identified the hazard. We thus emphasize that the learning curve demonstrated in NRT represents only those TBI survivors who were able to detect the hazard rather than all individuals in the TBI survivors group. Those survivors of TBI who did respond to a hazard might have better learning and prediction ability resources than did TBI survivors who failed to respond. The inherent limitations of both the response probability and NRT measures demonstrate the importance of measuring eye movement alongside behavioral response data. We suggest caution should be taken if the results are interpreted merely on the basis of behavioral performance outcomes. We further suggest that future studies focus on differences in HA skills that might appear within a group of individuals with moderate-to-severe TBI.

Conclusion

The current study serves as preliminary evidence of impaired repetitive learning of HA among survivors of moderate-to-severe TBI in a subacute phase. Repetitive exposure to the same hazards resulted in enhanced ability among noninjured control drivers to search for hazards in the correct location when repeatedly observing unmaterialized and hidden hazards. In contrast, study participants with moderate-to-severe TBI did not benefit from a repetitive presentation of hazardous situations. These initial findings signal the need for further research to clarify the relationship between TBI and HA training that should be considered as part of driving rehabilitation after TBI.

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