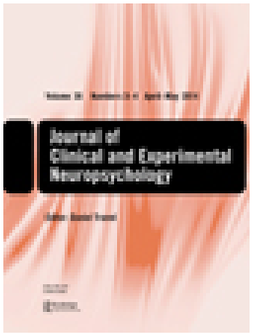

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Journal of Clinical and Experimental Neuropsychology

ISSN: 1380-3395 (Print) 1744-411X (Online) Journal homepage: https://www.tandfonline.com/loi/ncen20

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To cite this article: Yishai Deitcher, Yaron Sachar & Eli Vakil (2019): Effect of eye movement reactivation on visual memory among individuals with moderate-to-severe traumatic brain injury (TBI), Journal of Clinical and Experimental Neuropsychology, DOI: 10.1080/13803395.2019.1704223

To link to this article: https://doi.org/10.1080/13803395.2019.1704223

JOURNAL OF CLINICAL AND EXPERIMENTAL NEUROPSYCHOLOGY
https://doi.org/10.1080/13803395.2019.1704223

Effect of eye movement reactivation on visual memory among individuals with moderate-to-severe traumatic brain injury (TBI)

Yishai Deitcher[a], Yaron Sachar[b] and Eli Vakil[a]

[a]Psychology Department, Bar-Ilan University, Ramat-Gan, Israel; [b]Brain Injury rehabilitation, Loewenstein Hospital, Raanana, Israel

ABSTRACT

Objective: Previous research has shown that when individuals are asked questions referring to previously seen visual stimuli, their eye movements spontaneously return to the visual area where the stimuli were first seen. This recurring eye movement phenomenon has been shown to assist the memory retrieval of visual images. Individuals with moderate-to-severe traumatic brain injury (TBI) typically suffer from visual memory deficits as well as difficulty in spontaneously initiating mnemonic strategies. Perhaps TBI patients have trouble employing the eye movement reactivation strategy, thus further contributing to the visual memory deficits so prevalent among this population.

Method: In this study, 27 healthy individuals and 27 patients with moderate-to-severe TBI from the Lowenstein Rehabilitation Hospital participated in a memory task. Participants were first exposed to stimuli and were then asked questions about the displayed stimuli. The testing session was conducted for each participant under two conditions: (1) while eyes were free to move over the screen; (2) while eyes were fixated.

Results: Study findings show that the control group significantly benefitted from the free viewing in comparison to the fixed viewing condition, while this effect was absent among the TBI group. This was corroborated by eye tracking data showing that participants with TBI showed a minimal tendency to reactivate eye movements effectively, as occurs among the healthy group.

Conclusions: The research findings expand our comprehension of visual memory among the TBI population, presenting rehabilitation health clinicians with new directions in understanding visual memory deficits.

ARTICLE HISTORY
Received 26 May 2019
Accepted 8 December 2019

KEYWORDS
Visual memory; eye tracking; TBI

Abundant research has shown that when recalling a visual scene from memory, individuals' spontaneous eye movements closely reflect the movements made during their initial exposure to the scene (Brandt & Stark, 1997; Johansson, Holsanova, & Holmqvist, 2006; Laeng & Teodorescu, 2002; Martarelli & Mast, 2013). For example, Brandt and Stark (1997) recorded spontaneous eye movements occurring while viewing irregularly-checkered diagrams, and during a later session of imagining the same picture. They have shown that the later eye movements closely reflected the content and spatial proportions of the original picture or scene.

This eye movement reactivation phenomenon has been demonstrated even in the presence of a blank screen during the retrieval session (Brandt & Stark, 1997; Johansson et al., 2006; Laeng & Teodorescu, 2002; Spivey & Geng, 2001). The role of such eye movements can be explained by two logical possibilities: (1) they serve a functional role facilitating retrieval of visuospatial information, or (2) they are merely an epiphenomenal manifestation and do not play an active role in memory facilitation. In other words, do these recurring eye movements assist memory retrieval of the visual images, or are they simply a by-product of the initial exposure?

Proponents of the functional role of eye movements have speculated that restricting reenactment of eye movements by maintaining gaze fixation, should hinder ability to remember the visual stimuli. Indeed, various studies corroborate this assumption, showing that when interfering with free eye movement during the retrieval session, the visual memory is hampered (Ferreira, Apel, & Henderson, 2008; Johansson, Holsanova, Dewhurst, & Holmqvist, 2012; Johansson & Johansson, 2014; Laeng, Bloem, D'Ascenzo, & Tommasi, 2014). Hence, the mnemonic advantages of eye movement reactivation seem quite clear. The facilitation effect of eye movement reactivation could be understood as an effect of reenacting the spatial location of the stimulus that serves as a retrieval cue. Inhibiting the ability to retrieve the same eye movement pattern diminishes an individual's visual memory, as seen above. It is thus possible to assume that disability in retrieving the same eye movement pattern will account

CONTACT Eli Vakil vakile@mail.biu.ac.il Department of Psychology, Bar-Ilan University, Ramat-Gan 52900, Israel

for declined visual memory abilities, due to failure to benefit from this mnemonic advantage.

Studies have shown that individuals sustaining traumatic brain injury (TBI) display an inferior ability to remember visual stimuli (for review, see Vakil, 2005). Specifically, patients with severe TBI displayed an impairment performing The Shum Visual Learning Test (SVLT), and were found to learn visual stimuli at a slower rate (Shum, Harris, & O'Gorman, 2000). Other studies have shown the visual memory index derived from the Wechsler Memory Scale-Revised (WMS-R) among individuals with TBI to be inferior in comparison to controls (Reid & Kelly, 1993; Zec et al., 2001).

Additionally, patients with moderate-to-severe TBI generally seem to have difficulty initiating efficient learning and memory strategies (Blachstein, Vakil, & Hoofien, 1993; Vakil, 2005; Vanderploeg, Crowell, & Curtiss, 2001). This difficulty is especially pronounced when patients are expected to utilize mnemonic strategies spontaneously, that is to say, at their own initiative without instruction or guidance (Tyerman & King, 2009). In contrast, patients can benefit from guided mnemonic strategies, which can be efficiently utilized when given proper instruction (Mateer & Sira, 2006; Sumowski et al., 2010). Considering eye movement reactivation as a subconscious mnemonic strategy, it thus seems logical to posit that while patients with moderate-to-severe TBI may utilize this strategy under specific instruction from others, they would not tend to initiate such a strategy independently.

As we see, among many other typical symptoms, people with moderate-to-severe TBI suffer from visual memory as well as difficulty in initiating learning strategies spontaneously. Is it possible that these two phenomena are related to some degree? Perhaps visual memory deficits can be explained partially, as resulting from a diminished tendency to spontaneously employ eye movement reenactment during tasks involving visual memory. While eye movement reactivation seems to assist healthy individuals to remember memory stimuli, failure to utilize eye movement reenactment would undermine this facilitation. It is quite conceivable that difficulty in reactivating eye movements spontaneously may play an important role, contributing to the visual memory deficits so prevalent among the TBI population.

Another possibility to consider is that inferior visual memory among patients with TBI may stem from oculomotor deficits, also known to be significant among the TBI population. In their review and meta-analysis Mani, Asper, and Khuu (2018) have demonstrated long lasting oculomotor deficit following TBI, which may be associated with various cognitive deficits observed in this population. Studies have hitherto focused on healthy populations, and have shown that the reenactment of eye movements does indeed support visual memory retrieval. These studies found that fixating the gaze of participants indeed hinders their ability to remember the visual stimuli, by preventing the memory facilitation produced by eye movement reenactment. The present study will investigate this effect among patients sustaining TBI, a population whose visual memory is generally hampered.

In terms of behavioral results, it is predicted that overall recall of stimuli features as well as their spatial direction will be impaired in individuals following TBI, compared to controls. Furthermore, we expect to find an interaction between viewing condition (free vs. fixed) and group (control vs. TBI), hypothesizing that the memory advantage under free viewing compared to fixed viewing condition will be profoundly greater among the control group than among the TBI group.

In addition to the behavioral results, we monitored participants' eye movements using an eye-tracking device, thus enabling us to associate the behavioral findings of participants with their corresponding eye movement patterns. For the control group, it is predicted that under the free viewing condition their eye movements will be more focused on the original location of the stimulus about which they are asked than on other areas of the screen. Furthermore, we predict a correlation between focusing duration on the original location and correct recall of stimuli features and direction. Our predictions regarding eye movements of individuals that have sustained TBI are derived from our alternative hypotheses as to the source of impaired visual memory following TBI. Thus, according to the hypothesis that visual memory impairment following TBI stems from their impaired ability to initiate or utilize a strategy to facilitate their memory, we expect to find a relatively similar profile of eye movements in individuals with TBI and controls, despite the formers' memory impairment. However, if their visual memory impairment stems from their oculomotor deficit, we would expect to find an abnormal eye movement pattern that is associated with their memory performance.

This study pioneers in investigating the mnemonic effect of eye movement reactivation among populations with memory difficulties. The results of this study can shed light on understanding another possible source of visual memory deficits among patients with TBI. Moreover, the results of this study may have clinical implications for individuals with TBI, thus developing and providing strategies based on eye movements in order to enhance the visual memory capabilities of this population.

Method

Participants

A group of healthy young adults and a group of patients with moderate-to-severe TBI participated in the study. The control group of healthy adults consisted of 27 participants (25 males and 2 females), whose ages ranged from 18 to 50 years (M = 32.54). Among them, 17 individuals participated in return for a payment of 20 NIS (~$6 US), and 10 of the participants were undergraduate students at Bar-Ilan University, who took part in the experiment to fulfill academic requirements. The experimental group of patients with TBI consisted of 27 participants (25 males and 2 females), whose ages ranged from 19 to 50 years (M = 31.75). The Glasgow Coma Scale of patients with TBI ranged from 3 to 12 (M = 7.74), days of unconsciousness ranged from 0 to 51 (M = 16.37), and time after onset (in days) ranged from 38 to 210 (M = 80.63). Based on the above measures (as shown in Table 1), the patients were classified as having sustained moderate-to-severe TBI.

Participants from the experimental group were not to be rewarded for participation, which they understood prior to the experiment. The salient minority ratio of female participants is in accordance with the substantial male predominance of the TBI population (Siman-Tov et al., 2016), and the gender parameter of the control group was respectively matched, in addition to parameters of age and level of education. Independent-sample t-tests found no significant differences between the control group and the TBI group for age (M = 32.54, SD = 10.56; M = 31.75, SD = 11.67, respectively) $t(52) = .26$, $p = .79$, or for years of education (M = 14.18, SD = 2.47; M = 13.11, SD = 2.31, respectively), $t(52) = 1.65$, $p = .11$.

Table 1. Participant characteristics of the TBI experiment group.

Gender	Age	Years of Education	Glasgow Coma Scale	Days of unconsciousness	Time after onset (days)
Male	49	12	7	6	86
Male	42	15	9	1	58
Male	43	19	7	5	114
Male	48	12	7	21	38
Male	44	10	7	16	78
Male	21	12	10	0	131
Male	19	12	12	22	53
Male	20	12	6	4	39
Male	29	12	9	10	77
Male	21	12	6	7	107
Male	31	12	7	7	56
Male	40	12	11	14	138
Male	19	12	3	30	56
Female	20	12	6	14	61
Male	50	12	11	27	51
Female	23	12	6	14	210
Male	26	15	7	14	93
Male	39	12	5	30	114
Male	21	12	4	51	52
Male	23	12	3	28	73
Male	20	12	10	21	45
Male	46	12	11	0	63
Male	19	12	6	14	91
Male	30	12	12	1	79
Male	24	8	10	45	91
Male	40	19	12	1	47
Male	50	15	5	30	76

Participants in the experimental group were patients admitted to The Brain Injury Rehabilitation Ward in Loewenstein Rehabilitation Hospital. The patients were selected by the medical staff of the ward, excluding patients with severe psychiatric problems, substance abuse and patients with preexisting neurological or cognitive disorders. Moreover, participants in the experimental group possessed the ability to follow instructions, based on the assessment of the medical staff of the Brain Injury Rehabilitation Ward. All participants had normal or corrected-to-normal vision. Participants in both groups were proficient in Hebrew. Among the experimental group of patients with TBI, five were excluded due to difficulties of eye gaze and inability to calibrate eye positions, while three were excluded due to cognitive issues, manifested in significant difficulty to comprehend instructions. Among the control group, two were excluded due to inability to calibrate eye positions. Moreover, one control group participant was included in the behavioral analysis yet excluded from the eye movement analysis, since the eye movement recording was found to be faulty. Since participants from the groups were matched (based on age and education level), the corresponding TBI group participant was also included in the behavioral analysis but not in the eye movement analysis. All participants signed a consent form. The experiment was approved by the Helsinki Committee of Loewenstein Rehabilitation Hospital.

Instruments

Eye tracker

Horizontal and vertical coordinates of gaze direction were collected with a Remote Eye Tracking Device from Senso-Motoric Instruments, with a temporal resolution of 120Hz binocular and a spatial resolution of 0.03°. A camera was placed in front of the monitor below eye level and 45 cm from the participant, attached to an infrared light source to illuminate the cornea, so that the camera records the corneal reflection. Since the camera automatically compensates for small head movements, no head restraint was used. We first calibrated participants' eye position at the beginning of each session, by focusing the camera on the participant's right eye and having them focus their gaze on nine points dispersed along the screen. These positions were recorded as the eye gaze targets.

Visual stimuli

The pictures were selected from an online database (www.clipart.com) with a resolution of 280 × 262 pixels, consisting of 12 animals and 12 vehicles. All stimuli pictures in each category were similarly familiar.

Task and procedure

For the control group, the procedure took place in the Eye Movement Laboratory, at the Gonda Multidisciplinary Brain Research Center, Bar-Ilan University. For the experimental group, the procedure took place in The Brain Injury Rehabilitation Ward in Loewenstein Hospital. For both groups, the experiment was conducted in a room with normal ambient illumination, and the participants were seated 70 cm from a 32LG10R color monitor on which the stimuli were displayed. E-Prime software controlled the stimulus display and linked the timing of stimulus presentation with the computer that recorded eye movements. A standard eye tracker calibration routine was initiated at the beginning of the experiment, as detailed above in the previous section.

The experimental paradigm was based on Johansson and Johansson (2014), Johansson et al. (2012) and Laeng et al. (2014), described as follows: Each participant performed the tasks under two conditions: free viewing and fixed viewing (explained hereinafter), while each condition was comprised of an encoding stage and a testing stage. During each encoding stage (for both viewing conditions), participants were exposed to two categories of six visual stimuli distributed over a 3*3 grid on the screen (as shown in Appendix A). The cell measured 9.5*5.5 cm, while the entire grid measured 28.5*16.5cm. Each stimulus constituted a picture of either an animal or a vehicle, presented subsequently within each category (presentation order of categories was randomized). The pictures were displayed one by one, each for a total of three seconds (as shown in Appendix B), and the six pictures of the same category appeared simultaneously on the grid for a total of three seconds (as shown in Appendix C). This differs from the study of Johansson and Johansson (2014), which presented participants with multiple stimuli simultaneously and divided the screen area into four quadrants, presenting six items of a specific category in each quadrant. The current study presented participants first with individual stimuli, one at a time (as in the experiments by Laeng et al., 2014), and then all six items belonging to a certain category distributed along the entire screen. We believe our method ensures that participants pay attention to each stimulus.

Each participant performed the experiment under two conditions: free viewing and fixed viewing. Under both conditions, participants were free to move their eyes during encoding. However, during the testing stage of the fixed viewing condition, participants were instructed to maintain their gaze on the central fixation cross hairs at the center of the blank screen (as shown in Appendix D); under the free viewing condition, participants were free to move their eyes during the testing stage. The presentation order of viewing condition was randomized over the participants. See Figure 1 for a visual diagram of the experimental paradigm.

During each testing stage condition, participants heard 36 prerecorded statements of a female voice (2,500–4,500 milliseconds in length) consisting of two types: 24 statements concerning the stimuli features of the encoding stage (e.g., "the car was red") followed by 12 statements concerning the spatial relationship between two objects of the same category (e.g., "the ship was located to the right of the bicycle"). Participants were instructed to determine whether each statement was true or false by pressing a keyboard button. Both types of statements referred equally to the two categories (animals and vehicles). There was an equal number of true and false statements. Overall, during the experiment each participant listened to 72 statements, all spoken by a female voice in Hebrew. Participants were given eight seconds to respond after each statement. After completing both viewing conditions (free and fixed), a debriefing took place.

Results

In the current section, we report the behavioral results and the eye movements results obtained in the present study. The behavioral results describe the effect of TBI on the visual memory performance of individuals, in contrast to healthy control participants, for both free and fixed viewing conditions. In the following section, we compare the eye movements found among participants from these two groups, and investigate how these movements interact with the behavioral results.

Behavioral results

Item-feature memory

A Kolmogorov-Smirnov test indicates that the percentage of correct answers under both the free viewing and fixed viewing conditions do not follow a normal distribution, $D(54) = 0.17$, $p = 0.001$ and $D(54) = 0.14$, $p = 0.008$, respectively. Therefore non-parametric tests were conducted to analyze the difference in the percentage of correct answers, between the groups (TBI, control) and between the Viewing conditions (free viewing vs. fixed viewing), the former is a between subjects condition and the latter is a within subjects condition. A Mann-Whitney test indicated that the percentage of correct answers was greater for

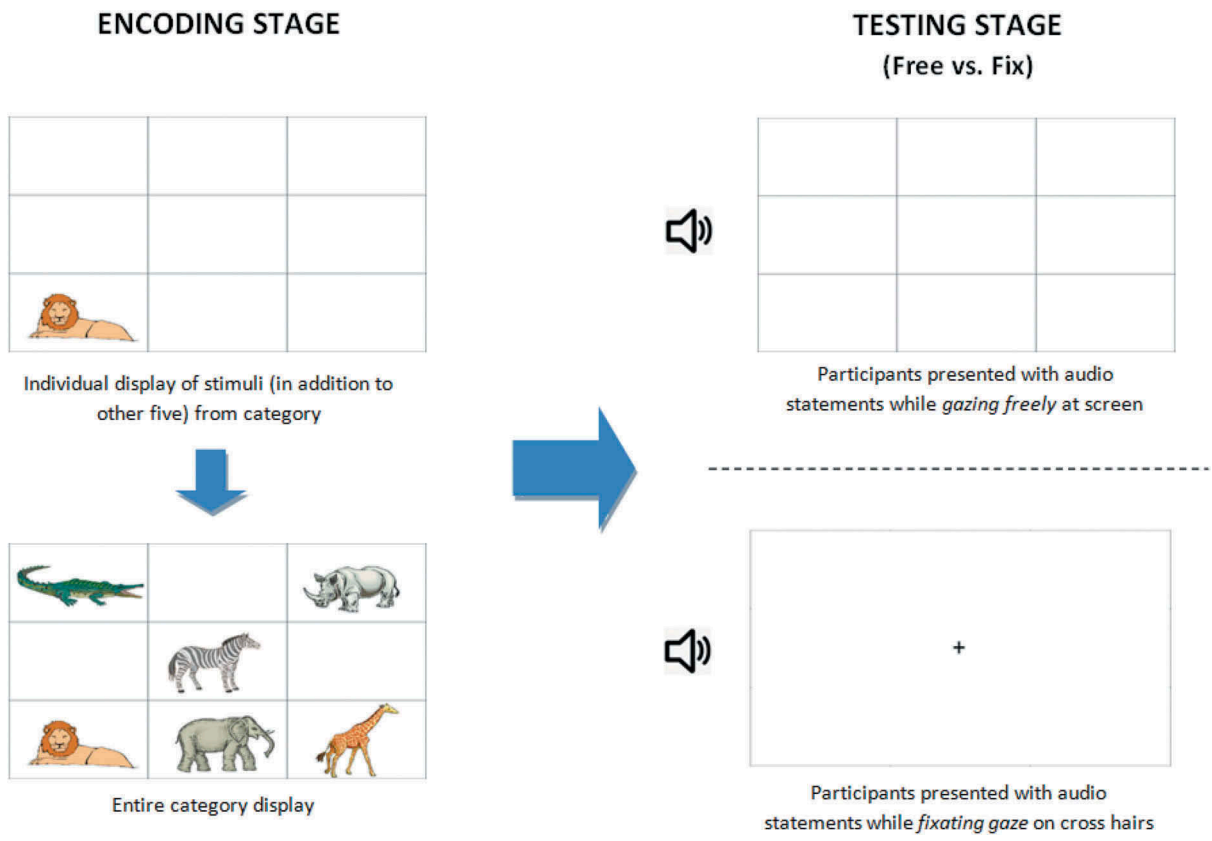

Figure 1. Visual diagram presenting the two stages of the experiment. During the encoding stage, participants were shown six images from a category one at a time, following display of the entire category simultaneously. Under each experimental condition (free vs. fixed), two categories were presented (12 stimuli per condition). During the testing, each participant was presented with 24 statements referring to *features* of the stimuli, while 12 statements referred to the *spatial* relationship between two stimuli. Participants were instructed to determine whether the statement was true or false. Under the fixed viewing condition, participants were instructed to determine the statement's accuracy while fixating their gaze on cross hairs; under the free viewing condition, participants were not instructed to do so. Each participant completed the experiment under both conditions.

the control group (Mdn = 83%) than for the TBI group (Mdn = 75%) under the free viewing condition, U = 541.00, p = .002. However, under the fixed viewing condition the control group (Mdn = 75%) and the TBI group (Mdn = 71%), did not differ significantly, U = 427.50, p = .27. A Wilcoxon Signed-ranks test indicated that for the control group the percentage of correct answers was greater under the free viewing condition (Mdn = 83%) than under the fixed viewing condition (Mdn = 75%), Z = 40.50, p = .001. However, for the TBI group the percentage of correct answers under the free viewing condition (Mdn = 75%) compared to the fixed viewing condition (Mdn = 71%), was not significantly different Z = 99.50, p = .58 (Figure 2).

Item-location memory

A Kolmogorov-Smirnov test indicates that the percentage of correct answers under both the free viewing and fixed viewing conditions do not follow a normal distribution, D(54) = 0.14, p = 0.011 and D(54) = 0.15, p = 0.003, respectively. Therefore, non-parametric tests were conducted to analyze the difference in the percentage of correct answers between the groups (TBI, control) and between the Viewing conditions (free viewing vs. fixed viewing); the former is a between subjects condition and the latter is a within subjects condition. A Mann-Whitney test indicated that the percentage of correct answers was greater for the control group (Mdn = 83%) than for the TBI group (Mdn = 67%) under the free viewing condition, U = 535.00, p = .003. However, under the fixed viewing condition, the control group (Mdn = 75%) and the TBI group (Mdn = 67%) did not differ significantly U = 426.00, p = .28. A Wilcoxon Signed-ranks test indicated that for the control group, the percentage of correct answers was greater under the free viewing condition (Mdn = 83%) than under the fixed viewing condition (Mdn = 75%), Z = 74.50, p = .031. However, for the TBI group the percentage of correct answers under the free viewing condition (Mdn = 67%) compared to the fixed viewing condition (Mdn = 67%), was not significantly different Z = 151.00, p = .98.

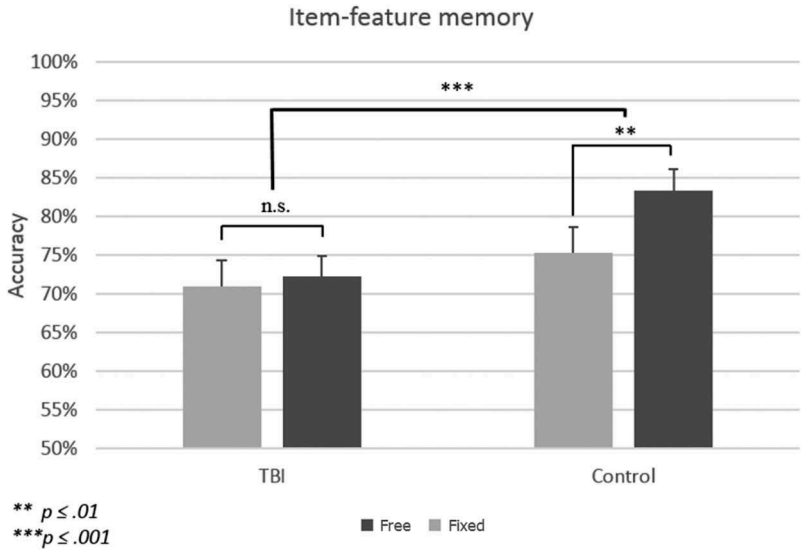

Figure 2. Average accuracy percentage of TBI vs. healthy participants, in both viewing conditions, during the item-feature memory test. Error bars represent standard errors.

In sum, findings indicate that the item-feature memory as well as Item-location memory performance of the TBI group was inferior to the control group's performance. In addition, the control group significantly benefited from the free viewing condition in comparison to the fixed viewing condition, while this effect was not found among the TBI group (Figure 3).

Eye movement results

We now analyze the eye movement data from the experiment. First, we examined the eye movements of participants under the fixed viewing condition, to confirm they were following instructions to focus on the central fixation cross hairs, thus validating our research assumption of eye gaze manipulation. Then, we compared the eye movements between participants of the two groups and investigated how they interacted with the behavioral results described above. Essentially, we analyzed participants' eye movements during the free viewing condition of both encoding and testing stages, with the purpose of understanding whether eye movement reactivation occurred among each group. Moreover, we analyzed how reactivation influenced the accuracy of visual memory, for both measures of item-feature memory and item-location memory.

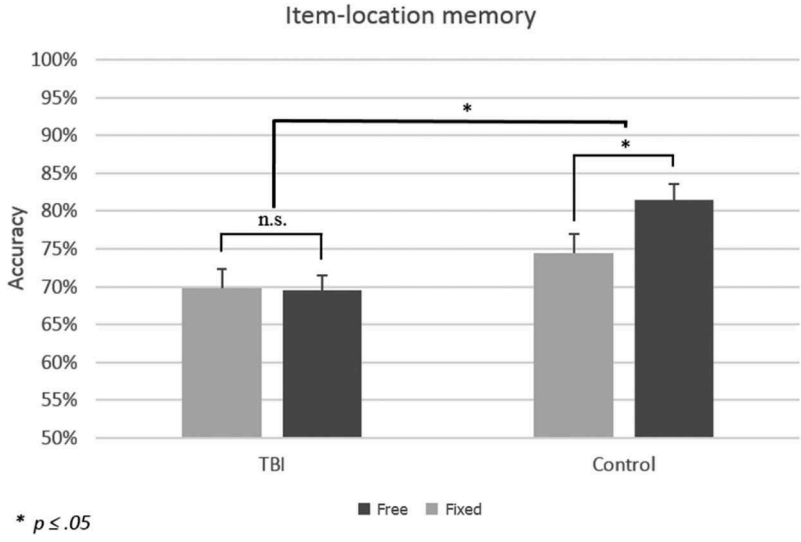

Figure 3. Average accuracy percentage of TBI vs. healthy participants, in both viewing conditions, during the item-location memory test. Error bars represent standard errors.

Fixed viewing condition: Analysis of dwell time on the fixation cross hairs

Eye movements were measured by means of dwell time (DT) percentage on the relevant AOI (area of interest). The AOI size was defined as the central cell itself where the cross hairs appeared (9.5*5.5 cm). DT percentage is calculated as the sum of fixations and saccades on a specific AOI, as a percentage of the total fixations and saccades. During the fixed viewing testing stage, participants were instructed to focus on the cross hairs positioned at the center of the screen. In this section, we compare the average DT percentage of participants on the central fixation cross hairs, compared to the rest of the screen area. A mixed-design 2 × 2 ANOVA with repeated measures was performed for the average DT percentage of participants, with Group and AOI (center, other) as independent measures. The average DT percentage here is calculated from the total eye movements of participants, including those other than the AOIs (therefore the sum of both central and other AOIs equals less than 100).

The results revealed a main effect of AOI, $F(1, 52) = 1727.35$, $p < .001$, $\eta_p^2 = .97$, with the average DT percentage of center AOI ($M = 83.17\%$, $SD = 10.98$) being significantly greater than the average DT percentage of all the other AOIs combined ($M = 13.94\%$, $SD = 3.96$). While no main effect for Group was found, a significant interaction was observed between AOI type and Group (view Figure 4), $F(1, 52) = 4.76$, $p < .05$, $\eta_p^2 = .09$, showing that while the average DT percentage on the central AOI was greater among the control group than among the TBI group, the groups' DT did not differ on the other AOIs.

Free viewing condition: Eye movement reactivation and relationship with accuracy of item-feature memory

We now consider the relationship between eye movements of participants during the encoding and testing stages, under the free viewing condition. Eye movements were measured by means of DT percentage on the relevant AOI where the stimulus was presented during the encoding stage. The AOI size was defined as the specific cell where the stimulus appeared (9.5*5.5 cm). A Pearson correlation coefficient was conducted at the stimuli-based level in order to assess the congruence of eye movements on the critical AOI between the initial encoding stage and the following testing stage, for each stimulus individually. According to our hypothesis and consistent with previous research, eye movements spontaneously return to the visual area where the stimuli was first seen (Brandt & Stark, 1997; Johansson et al., 2006); this analysis is therefore essential for our theoretical reasoning, and was conducted in the study by Laeng et al. (2014).

The analysis indicated that there was a significant association of eye movement between the encoding and corresponding testing stage, for both the control group ($r(192) = .30$, $p < .001$) and the TBI group, ($r(202) = .12$, $p < .001$). Using the Fisher r-to-z transformation, we found that this difference was statistically significant ($z = 3.23$, $p < .001$). An independent-sample t-test conducted at the stimuli-based level (after filtering out empty values, not including DT percentage equal to zero) found that the average DT percentage on the

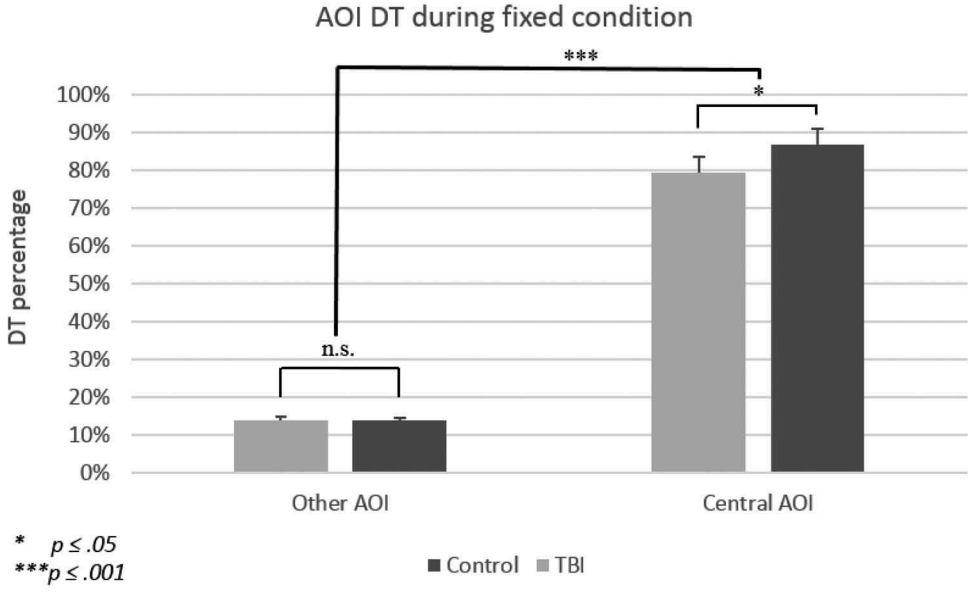

Figure 4. Average DT percentage of TBI vs. healthy participants on both central AOI (as instructed) and other AOIs during the fixed viewing condition. Error bars represent standard errors.

control group's critical AOI (M = 37.25%, SD = 30.98) was significantly higher than that of the TBI group (M = 26.20%, SD = 26.79), $t(310) = 3.32$, $p = .001$. However, this finding should be taken with caution, due to the relatively large variability among the DT percentage values.

We now describe the relationship between the degree of eye movement reactivation and the accuracy of item-feature memory under the free viewing condition. Specifically, for each participant we measured the degree of DT percentage on the relevant AOI location during testing, alongside the participant's accuracy level in answering the item-feature questions. The correlation coefficient indicated that for the control group, there was a significant positive association between eye movement reactivation and the accuracy of item-features memory, $r(23) = .54$, $p < .01$. In contrast, the above correlation for the TBI group was marginally significant ($r(25) = .33$, $p = .09$). It should be noted that two participants from the control group were identified as outliers due to their deviation (more than 2 SD from the average) and were filtered from the results (Figure 5).

Free viewing condition: Relationship between eye movement reactivation and accuracy of item-location memory

Here we focused on eye movement reactivation by comparing DT percentage on the relevant AOI between learning and testing stages. As conducted above for the item-feature memory parameter, we administrated a Pearson coefficient at the stimuli-based level, comparing DT percentage on relevant AOI between the learning and testing sessions for each stimulus presented (after filtering out empty values). Since the item-location statements include two components (e.g., "the *ship* was located to the right of the *bicycle*"), the DT percentage was calculated as a sum of both items in their relevant AOIs. The analysis demonstrated a significant correlation of eye movements per stimuli between their corresponding learning and testing stages under the free viewing condition, for both the control group ($r(192) = .19$, $p < .01$) and TBI group ($r(202) = .20$, $p > .01$). An independent-sample t-test conducted at the stimuli-based level found no significant difference of average DT percentage on the critical AOI between the control group (M = 42.01%, SD = 29.89) and the TBI group (M = 34.84%, SD = 29.70), $t(197) = 1.68$, $p = .10$.

We now consider the relationship between eye movement reactivation and accuracy for the item-location memory parameter under the free viewing condition. As in the above analysis, we measured the correlation between DT percentage at the critical AOI location during testing, and accuracy of answering the item-location questions. The current Pearson coefficient between the above measures was found to be non-significant for both TBI and control groups ($r(202) = .27$, $p = .18$; $r(169) = .10$, $p = .63$, respectively).

In sum, results from the fixed viewing condition demonstrated that during the testing stage of the fixed viewing condition, participants focused as instructed on the central AOI (where cross hairs were shown) more than all other screen areas combined. Moreover, it was found that the control group focused more on the central AOI than the TBI group.

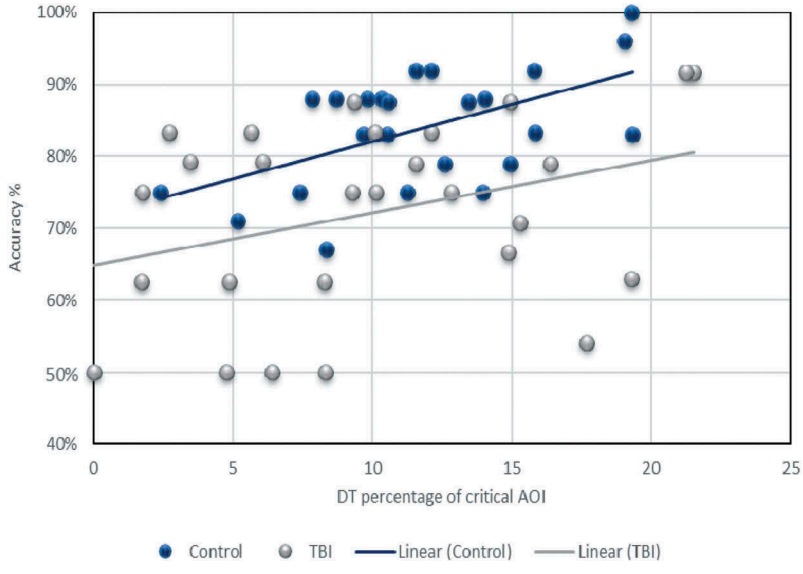

Figure 5. Scatter plot for accuracy percentage correlated with relative dwell time (DT) percentage on critical AOI during recall, for the control group ($p < .01$) and TBI group ($p = .09$).

The eye movement results from the free viewing condition showed that there was a significant correlation of relative DT per item, between the learning and testing stages, and for item-feature memory found among both the control group ($r(192) = .30$, $p < .001$) and the TBI group, ($r(202) = .12$, $p < .001$). When contrasting groups, the correlation among the control group was significantly stronger than that obtained among the TBI group ($z = 3.23$, $p < .001$). Moreover, we found a substantial relationship between eye movement reactivation and accuracy performance for the control group ($r(23) = .54$, $p < .01$), but only a marginally significant relationship for the TBI group ($r(25) = .33$, $p = .09$).

Regarding the item-location index, a significant correlation was found between the corresponding eye movements during encoding and testing stages for both the control group ($r(192) = .19$, $p < .01$) and TBI group ($r(202) = .20$, $p > .01$), but there was no substantial difference between the groups ($t(197) = 1.68$, $p = .10$). Additionally, the results did not provide a substantial relationship between eye movement reactivation and accuracy performance for the item-location statements for either TBI or control groups ($r(202) = .27$, $p = .18$; $r(169) = .10$, $p = .63$, respectively).

Discussion

The present study aimed to address the role of recurring eye movements on visual memory among TBI patients, by implementing eye-tracking technology to monitor oculomotor movement. Altogether, the findings presented support our hypotheses and provide us with a new understanding of visual memory deficits among moderate-to-severe TBI individuals. As expected, our results confirm that the TBI group's visual memory performance is inferior to that of the control group, for both item-features memory and item-location memory. These results corroborate previous research (Shum et al., 2000; Vakil, 2005) showing that patients suffering from moderate-to-severe TBI display substantial visual memory impairment.

Moreover, the findings of the current study have shown that fixating eye movements limited the facilitatory effect of eye movement reactivation for the questions referring to item-features. Additionally, the analysis found an interaction between Group and Viewing conditions, showing that while the free viewing condition of the healthy participants significantly reinforced their performance in comparison to the fixed viewing condition, this effect was not found among the TBI group. While findings did not exhibit a main effect of viewing condition for item-location memory, performance was significantly lower among the control group, but not among the TBI group, thus providing us with conclusions similar to those found for the item-feature memory results. These findings are congruent with previous research conducted on healthy participants, showing that fixating eye movement during testing inhibited their ability to remember visual information of previously learned stimuli (Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014). However, a study manipulating eye movements of patients with TBI has yet to be conducted, and of our study findings show that, in contrast to healthy individuals, fixating gaze has no significant effect. We expected that the fixation manipulation would affect both groups, albeit to a lesser degree among the TBI group. Results indicated that gaze manipulation affected the groups differently, but more significantly than we expected. While spontaneous eye movement during testing significantly facilitated visual memory, this effect was not even observable among individuals with TBI. This is noteworthy, since eye movement reactivation substantially consolidates visual memory; the absence of this facilitatory component may account at least partially for a meaningful proportion of visual memory deficits among patients with TBI.

The eye movement data enabled us to reach important insights regarding the phenomenon of eye movement reactivation during the testing stage. In congruence with previous research (Johansson & Johansson, 2014), we found that during the testing stage, under the free viewing condition, there was a reenactment of encoding stage eye movements; this was found for both types of visual memory and among both control and TBI groups. In accordance with our hypothesis, our results showed that for the item-feature memory, the reenactment of eye movements during testing was more profound among the control group, in comparison to the TBI group. However, as expected, we did not find this difference for item-location memory. This finding will be referred to below.

By extrapolating the eye movement data, we were able to appreciate the relationship between eye movement reactivation and memory performance, among both groups. This provided us with additional understanding, complementary to the analysis presented above comparing the behavioral results of the two viewing conditions. We learned from the eye movement data that among the control group, a significant correlation exists between eye movement reactivation during testing and item-feature memory performance. This is consistent with previous research findings, conducted on healthy participants (Johansson et al., 2014). Among the TBI group, however, this relationship was marginally significant.

In the introduction, we presented two alternative explanations of the inferior visual memory performance of patients with TBI: first, that it stems from oculomotor deficits previously shown to be associated with various cognitive deficits observed in this population (Mani et al., 2018). Thus, individuals with TBI will show an abnormal pattern of eye movement that prevents them from benefiting from the eye movement reenactment. Second, a potential explanation is that even when eye movement reactivation is present among people with TBI, it is utilized relatively ineffectively. This is consistent with previous studies showing that patients with moderate-to-severe TBI seem generally to have difficulty initiating efficient learning and memory strategies (Blachstein et al., 1993; Vakil, 2005; Vanderploeg et al., 2001).

The eye movement data showed us that there was a small difference between the groups' DT percentages when focusing on the central cross hairs during the fixed viewing condition. It is possible that oculomotor deficits, prevalent among the TBI population, would explain why the TBI group fixated on the central cross hairs less than the control group. However, this difference is quite small, and altogether participants with TBI were able to focus on the appropriate AOI. Furthermore, a significant association was found between eye movements in the learning phase and testing phase on item feature memory for both groups. However, it was more pronounced for the control group than the TBI group. So again, their pattern of eye movement is similar to, but not quite as exact as for that of controls. Thus, although these oculomotor differences do exist between controls and TBI participants, it does not seem to explain the memory impairment observed in the TBI group. That is because when they were able to reenact the original eye movement, it did not predict memory accuracy as it did in the control group. This finding provides more support for the alternative interpretation, namely, that the TBI group has difficulties in efficient utilization of eye movement reinstatement to support their visual memory.

This proposed model is consistent with previous research that demonstrated how individuals with moderate-to-severe TBI display a mitigated tendency to initiating learning and memory strategies; even when such strategies are implemented, they are often applied ineffectively (Vakil, 2005; Vanderploeg et al., 2001). This is especially pronounced when the learning strategy is initiated spontaneously, without instruction or guidance (Tyerman & King, 2009). Considering eye movement reactivation as a spontaneous mnemonic strategy, this model aptly illustrates how and why people with TBI fail to benefit from eye movement reactivation, as compared to their healthy counterparts.

As mentioned previously, the current study did not find a significant difference in eye movement reactivation between the control and TBI groups. Additionally, no significant correlation was found between eye movement reactivation and item-location memory performance for either group, contrary to our research assumptions. Furthermore, the results did not support our suppositions that spatial location memory would be affected by viewing condition. In sum, it seems that while our study expectations were robustly upheld with respect to item-feature memory, they lacked such support from the item-location memory analysis.

Our conclusion is somewhat in contrast with the findings of Johansson and Johansson (2014); according to whose results gaze manipulation had a stronger effect on item-location memory than item-feature memory. This discrepancy may stem from a key difference between the stimuli presentation method of each study. While our study presented six items belonging to a certain category distributed along the entire screen, the above study divided the screen area into four defined quadrants, presenting six items of a specific category in each quadrant (altogether 24 items). We believe that our method measures item-location memory more accurately since the global view of interest is that of the category, not the entire array of stimuli from all categories. One may argue that participants in the above study processed each quadrant as one complex stimulus, while the individual items were processed as constituents of this stimulus.

In our opinion, the explanation for the divergent results between the parameters of item-features and item-location may lie in the inherent difference between the statement-questions of each memory type. The item-features statement referred to a feature of *one* stimulus (e.g., "the *car* was red"), which prompted the participant, consistent with our assumptions and findings, to focus on the screen area where the stimulus was previously displayed. However, the item-location statement referred to the relative positioning of *two* stimuli (e.g., "the *ship* was located to the right of the *bicycle*"); loading the statement with an addition stimulus, may have encumbered the participant to reactivate eye gaze on both AOIs. Moreover, this statement type is more complicated from an analytic perspective as well, since two reference points are engaged in such a statement, thus clouding the direct correspondence between the learning and testing eye movements. This may also have contributed to obfuscating the referred correlations.

It is well documented that most moderate-to-severe TBI patients are males (about 70%) (Siman-Tov et al., 2016). In the present study, the proportion of males was even higher than that (25 males and 2 females).

Unfortunately, that was the number of females with moderate-to-severe TBI hospitalized when this study was conducted. That should be considered as one of the of this study's limitations in terms of generalization of conclusions.

To conclude, our study found that fixating eye movements during testing had a significant negative effect on the visual memory abilities of the control group, but not of the TBI group. This behavioral finding strongly supports our hypothesis that while recurring eye movements facilitate visual memory among the healthy population during free gaze, such movements are somewhat absent among the moderate-to-severe TBI population. The eye tracking data enabled us to examine participants' eye movements directly during the experiment, beyond the behavioral data. These findings further cement our thesis by showing us at the oculomotor level that individuals with moderate-to-severe TBI exhibit effective recurring eye movements to a lesser extent than their healthy counterparts. It should be noted that this study is the first to investigate the mnemonic effect of eye movement reactivation among a group characterized with memory deficits, specifically the TBI population.

These findings present a new horizon of treating visual memory impairments among patients with TBI. As mentioned above, several studies have demonstrated that individuals with TBI have difficulties in initiating efficient learning and memory strategies (Blachstein et al., 1993; Vakil, 2005; Vanderploeg et al., 2001). However, when provided with a strategy and explicit guidance on how to implement it, they do show some benefit (Mateer & Sira, 2006; Sumowski et al., 2010). Thus, by guiding patients to be aware of visual stimuli positioning, in addition to encouraging them to focus on these areas during testing, rehabilitation clinicians may find groundbreaking possibilities to overcome visual memory deficits among patients with TBI.

Further research can address this question by testing whether initial guidance of patients to be conscious of stimuli positioning, for both learning and testing, can enhance visual memory abilities. If this is successfully demonstrated, future studies will determine whether this mnemonic strategy, following significant guidance of rehabilitation clinicians, could eventually be implemented efficiently and spontaneously in an independent manner.

Acknowledgments

We thank Ms. Myriam B. Dalla-Torre for programing the experimental task used in the current study. Moreover, her experience and comments greatly assisted the research.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Israeli Ministry of Defense, Rehabilitation Department under Grant number [203003-846].

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Appendices

Appendix A

Appendix B

		

Appendix C

Appendix D