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Direct and indirect measures of context in patients with mild-to-severe traumatic brain injury (TBI): The additive contribution of eye tracking

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ABSTRACT

Introduction: The facilitation of memory for target stimuli due to the similarity of context in the learning and testing phases is known as the "Context-Effect" (CE). Previous studies reported that TBI affects memory for contextual information when tested directly. However, the indirect effect of contextual information on memory of target (i.e., CE) is preserved. Several studies have demonstrated that CE is composed of multiple, distinct cognitive processes. The present study includes four context conditions to enable identification of the exact process affected by TBI. In addition, eye movements were monitored to test three hypotheses: first, that the TBI group's dwell time on target (DTOT) at encoding would be less than that of controls. Second, that DTOT at encoding would be more highly associated with recognition at test for the control group than for the TBI group. Third, that overall DTOT at encoding on new, as compared to old items ("repetition effect"), would be less pronounced for the TBI group as compared to controls.
Methods: Twenty-four patients with mild-to-severe TBI and 23 matched controls participated in this study. We presented participants with photographs of male faces shown wearing distinctive, trial-unique hats (yielding specific Target-Context pairing). Eye movements were recorded throughout the test task.
Results: Memory for faces following TBI is impaired compared to that of controls. The magnitude and pattern of CE are the same for both groups. The TBI group has a lower DTOT compared to that of controls. However, the relative length of DTOT in the various conditions is similar in both groups.
Conclusions: Behavioral results indicate that although the TBI group has impaired memory for faces, the CE pattern is similar to that of controls. Similarly, in terms of eye movements, although the TBI group focuses less on target, relations between the various conditions are similar in both groups.

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Context effect; eye tracking; TBI

Memory for information on which we focus in an attempt to remember (i.e., target) is improved when tested in the presence of the same learning context. This facilitatory effect of contextual information is referred to in the literature as "context effect" (CE) (Memon & Bruce, 1985; Vakil, Golan, Grunbaum, Groswasser, & Aberbuch, 1996). CE's have been studied in natural environments and are referred to as 'environmental context' studies, versus studies conducted in more artificial conditions that are referred to as "laboratory studies". The classical study by Godden and Baddeley (1975) in which they changed learning and testing contexts from land to underwater and vice versa, is an example of an "environmental context" study. In other "environmental context" studies, CE has been induced by changing classrooms between study and test (Fernandez & Alonso, 2001) (for a review, see Smith & Vela, 2001). Unlike the above examples of "environmental context" studies, in which the context is real and natural, in "laboratory studies" the target (to be remembered stimulus) as well as contextual stimuli are presented in a laboratory setting, typically on a computer screen. In such studies, target and context stimuli could be pictures of faces wearing hats, respectively (Dalton, 1993; Vakil, Raz, & Levy, 2007), or pairs of objects designated as target and the other as context (Levy, Rabinyan, & Vakil, 2008). While environmental studies have the advantage of being more ecologically valid, the laboratory studies are conducted under better-controlled conditions (e.g., exposure duration).

Traumatic brain injury (TBI) affects a wide range of cognitive domains (e.g., attention, processing speed, executive functions), but memory functioning reflects one of the most pronounced deficits (for review, see Canty, Shum, Levin, & Chan, 2014; Vakil, 2005). Context memory is one of the memory aspects examined in individuals who have sustained TBI. It has been demonstrated that individuals with TBI who exhibit memory impairments, including deficits when directly

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asked about contextual information (i.e., source memory), nevertheless benefit from context reinstatement at retrieval, which reflects indirect memory of contextual information. Patients affected by TBI were quite consistently shown to have the same magnitude of CE as that of matched controls, using various paradigms that tested CE (cf. Vakil, Blachstein, & Hoofien, 1991; re: temporal order judgment; cf. Vakil, Biederman, Liran, Groswasser, & Aberbuch, 1994, re: frequency judgment; cf. Vakil et al., 1996, re: perceptual context; cf. Vakil, Openheim, Falck, Aberbuch, & Groswasser, 1997, re: modality of presentation). In a more recent study, Barak, Vakil, and Levy (2013) have demonstrated how this preserved aspect of memory (i.e., CE) is expressed for cued and free recall in individuals with TBI.

Several studies have demonstrated that CE is not a unitary process but is rather composed of at least two distinct cognitive processes that form the association between Target and Context. The Item, Context Ensemble – ICE theory distinguishes between *item* which is memory of the item to be remembered (i.e., target), *associated context* which is the background information learned incidentally, *and ensemble* which reflects an integration of both the target and context stimuli (Murnane, Phelps, & Malmberg, 1999). Vakil et al. (2007) introduced a multifactorial model that distinguishes between *binding* (similar to *ensemble*) and *familiarity*. In addition, Vakil et al. introduced an additional component, *configural similarity*. This process explains the higher hit rate when the stimulus-array structure was repeated at test, even if an old target (face) appears in a new context (hat), compared to the condition in which an old target is presented with no context.

In order to make this distinction, at least four testing conditions of context are required. 1. *Repeat*, in which the exact context from the encoding phase is reinstated at test with the original target. 2. *Re-pair* or rearranged, in which an old target from the encoding phase is presented at test with an old context, but which is different than the original one presented with it. In addition, 3. *New context*, an old target presented with a new context that was not presented at the encoding phase, and 4. *No*, an old target presented in a blank background, which is neither picture nor word as context. In Repeat and Re-pair conditions, target and context stimuli have been presented in the learning phase. The only difference is that the same exact pair is now presented at the test phase in one condition (Repeat), while in the other condition (Re-pair) target and context were not originally presented together as a pair. Thus, the advantage of the Repeat over the Re-pair condition would suggest a specific binding (or ensemble) between target and context which yielded the CE. In contrast, should the Repeat and Re-pair condition yield the same CE, that would indicate that binding is not necessary to yield CE, and that familiarity with the old items is sufficient to produce CE. Furthermore, if the familiarity process yields CE, an advantage of the Re-pair condition over the New condition is predicted, due to the presence of two old elements (old target and old context) versus only one (only old target), respectively. The advantage of the New over the No condition reflects what Vakil et al. (2007) refer to as the *configural similarity* process. Previous studies, cited above, that tested the effect of TBI on CE did not use all four context conditions, and therefore could not conclusively determine whether the CE found in individuals with TBI is based on binding, familiarity or the configural similarity effect. Thus, to rectify this limitation of previous studies, that were unable to detect the exact process(es) affected by TBI, the present study included all four context conditions. Based on the literature regarding the effect of TBI on memory (for review, see Vakil, 2005) it is predicted that memory for target (i.e., faces) would be impaired compared to controls, because in this case memory is probed directly. However, the indirect effect of context on target memory (i.e., CE) is predicted to be similar to that of the controls.

Several memory studies have recently used eye tracking as an additional tool to provide information about underlying cognitive processes not always consciously available to the individual (for review, see Hannula et al., 2010). Regardless of the participant's accuracy on the recognition test, when compared to old stimuli, new stimuli would receive longer first and overall fixation duration, but fewer fixations. This is referred to in the literature as 'Repetition effect' (Chanon & Hopfinger, 2008; Hannula et al., 2010; Ryan, Hannula, & Cohen, 2007, but see Christie & Klein, 1995). Ryan, Althoff, Whitlow, and Cohen (2000) have shown that eye movement patterns distinguished between old and new pictures in the testing phase. Kafkas and Montaldi (2011) measured eye movements during incidental learning of a set of pictures. One of their interesting findings was that the number of fixations on a picture at the learning phase predicted the strength of its recognition. Similarly, Heisz, Pottruff, and Shore (2013) reported an advantage of females over males in recognition memory of faces. This advantage was associated with more fixations made on the faces during the learning phase. Thus, the conclusion from these two studies is that the duration of processing at encoding, as reflected by the number of fixations, predicts later recognition memory strength.

The well-documented fact that individuals who sustained TBI show CE to the same extent as controls does not necessarily indicate that the underlying cognitive processes are the same. Thus, in the present study, the Re-pair condition was added, which would allow us to identify the exact underlying cognitive process of the CE found with individuals who sustained TBI. In addition, by monitoring eye movements while performing the task, we would be able to address several questions about the learning and recognition processes of both groups. For example, both groups are asked to focus in the learning phase on the target stimuli (i.e., faces). But do the groups differ in the proportional attention allocated in the learning phase to the target stimuli (i.e., faces), compared to the context stimuli (i.e., hats)? Our hypothesis is that due to impaired selective attention following TBI (Virk, Williams, Brunsdon, Suh, & Morrow, 2015), dwell time on target (DTOT) at encoding would be higher for the control group compared to the TBI group. Moreover, it is predicted that DTOT at encoding would be more strongly associated with recognition at test for the control group than for the TBI group. Finally, it is predicted that overall DTOT at the test phase on new items will be greater than on old items (i.e., "repetition effect"). This effect is expected to be less pronounced in the TBI group than in the control group. Such findings could give us insight into the differences between the groups while performing the memory task.

Method

Participants

Two groups participated in the present study: a control group (non-brain damaged) and patients following TBI. The control group consisted of 23 individuals with normal or corrected vision. Sixteen individuals participated voluntarily, four participated in return for a payment of 20 NIS (~$6 US), and three of the participants were undergraduate students at Bar-Ilan University, who took part in the experiment to fulfill academic requirements. Their age ranged from 23 to 60 years (mean age 35.30). The group with TBI included 24 patients whose age ranged from 19 to 70 years (mean age 36.21). The groups' ages did not differ significantly, $t(45) = 0.233$, $p = 0.82$. Participants were recruited for the study from a population of patients admitted to the Loewenstein Rehabilitation Hospital (Israel), for rehabilitation following a traumatic brain injury. The time after onset ranged from 15 to 139 days (mean 55.25 days). The group consisted of patients with mild-to-severe TBI, estimated according to the Glasgow Coma Scale, ranging from 3 to 15 (mean 8.25), with a duration of Coma ranging from none to 33 days (mean 8.75 days). When recruited for the study, patients were at least two weeks after injury and all were beyond Post-Traumatic Amnesia (PTA), as evaluated by a multidisciplinary hospital team. Based on the tests conducted, patients' intellectual and linguistic functioning was at a level enabling adequate responsiveness to the task requirements. None of the participants had a history of alcohol, drug abuse, or psychiatric illness. Written informed consent was obtained from all participants. The study was approved as required by the Helsinki Committee at Loewenstein Rehabilitation Hospital.

Apparatus

Eye movements were recorded by the SensoMotoric Instruments (SMI) RED-M remote eye-tracker that allowed free head movements, with a sampling rate of 120 Hz and high accuracy of 0.8°. A 9-point calibration cycle at the beginning of the experiment provided a spatial resolution of 0.1°. A camera with an ultra-light source was placed in front of the laptop screen, below eye level, and approximately 60 cm from the participant.

Stimuli were presented on a 15.6" laptop screen, monitor driven at a refresh rate of 60 Hz and a resolution of 1,366 x 768 pixels, using the E-prime 2.0 software, which controlled and recorded the temporal parameters of the stimulus display, and linked the timing of stimulus presentation with the computer that recorded eye movements.

Materials

The task used in this study is the same one used previously in our laboratory (Vakil et al., 2007). Stimuli consisted of 112 color photographs of male adult faces, each with a resolution of 720 × 576 pixels (see Appendix A). All faces were photographed under the same light conditions and with neutral facial expressions. The pictures were taken with permission of the authors from the XM2VTS database (Messer, Matas, Kittler, Luettin, & Maitre, 1999). In addition, there were 112 color photographs of hats. These stimuli were randomly paired to form 64 face–hat study pairs (see Appendix B), and an additional 48 faces and 48 hats supplemented them to form the various test pair combinations. Eight types of face–hat photo pairs or face-only photos were presented at test, each forming a different test condition (see Appendix B):

(A) 8 of the originally studied pairs (Target Old, Context Old-Same; "Repeat" condition).
(B) 8 pairs in which a studied target face was presented in the context of a hat that had been seen

at study with a different face (Target Old, Context Old-Different; ‘Re-pair‘ condition).
(C) 8 pairs in which a studied target face was presented in the context of a new hat that had not been seen at study (Target Old, Context New; “New” condition).
(D) 8 studied target faces unaccompanied by any hat (Target Old; “No” condition).
(E) 16 new unstudied faces presented in the context of a hat that had been seen at study with a different face (Target New, Context Old).
(F) 8 pairs of new, unstudied faces and hats (Target New, Context New).
(G) 8 new unstudied faces unaccompanied by any hat (Target New).

Eye movement measures

All the pairs of face and hat slides contained two Areas of Interest (AOI), such as a face figure and a hat figure, and the only face slides contained just one AOI (face figure). The AOIs were created by drawing two polygonal AOIs as “face“ (i.e., target) and ”hat” (i.e., context) specifically for each stimulus. We did not use a fixed box because the area sizes of the various faces and hats were not identical, so we had to draw the boundaries specifically for each stimulus (see Appendix A).

The eye movement measure used in this study is Dwell Time, which is defined as the sum of durations of all fixations and saccades that hit the Area of Interest (AOI) from entry to exit (recorded in milliseconds). We then calculated the proportion (%) dwell time in the AOI “face” over the total dwell time (i.e., AOI “face” + AOI “hat” + AOI “white space”).

Procedure

At the encoding phase, face–hat pairs were presented on a laptop computer screen by E-prime (2.0) software for 4000 ms each. Between each pair, a cross was flashed in the middle of the screen for 1000 ms. Participants were instructed to remember the faces for a subsequent memory test.

The learning phase was followed immediately by the test phase. Participants were told that they would see studied and unstudied faces. They were asked to indicate by key press (“L“ key for a ‘yes’ response and ”A” key for a “no” response), as quickly and accurately as possible, if the face had been seen at study (Old) or not (New). Participants were instructed verbally to guess if they were unsure. They were then shown face–hat pairs or face-only photos (types A-G above) in randomized order. The rate of presentation of test trials was self-paced, with the response triggering the following trial. All responses were automatically recorded by the E-prime software.

Results

Behavioral data

In order to correct for multiple comparisons, we set the threshold for significance to $p < .01$.

Hit rate: Mixed ANOVA was conducted in order to test the effects of Context (Repeat, Re-pair, New, & No) and Group (Control & TBI), the former is a within-subjects factor and the latter is a between-subjects factor. The results showed that both main effects, Context, and Group, reached significance, $F(3, 135) = 28.14$, $p < 0.001$, $\eta_p^2 = .39$ and $F(1, 45) = 12.54$, $p < 0.001$, $\eta_p^2 = .22$, respectively. However, the interaction did not reach significance, $F(3, 135) = 0.96$ $p = 0.42$, $\eta_p^2 = .022$.

As can be seen in Figure 1, both groups show context effect, i.e., that the highest number of hits was under the Repeat condition, and the lowest under the No context condition. Overall, it can be seen clearly that the control group had a higher hit rate.

Post-hoc analysis using Bonferroni procedure was conducted in order to detect the source of the context effect. It was found that all context conditions differed significantly ($p < .001$) from each other with one exception, the difference between Re-pair and New (Repeat > Re-pair = New > No). This suggests that both groups showed the *binding* effect (Repeat > Re-pair) and the *configural similarity* effect, but not the *familiarity* effect (Re-pair = New) of context.

Eye movements

Learning phase

In order to examine our hypothesis that the group with TBI was less attentive to the target than the controls, we compared the percentage of DTOT between the groups. Therefore, we conducted a one-sided independent sample t-test which was marginally significant, $t(45) = -1.82$, $p = 0.04$. The percentage of DTOT spent by the group with TBI ($M = 78.35$, $SD = 14.05$) was less than the percentage of DTOT spent by the control group ($M = 85.07$, $SD = 10.99$).

An additional analysis was conducted in order to test the hypothesis that longer DTOT at the learning phase would lead to better recognition at test. Mixed ANOVA was conducted in order to test both groups' DTOT at encoding of the stimuli, which were eventually correctly recognized at test in the various context conditions (Repeat, Re-pair, New, & No). Context main effect reached significance $F(3, 135) = 6.51$,

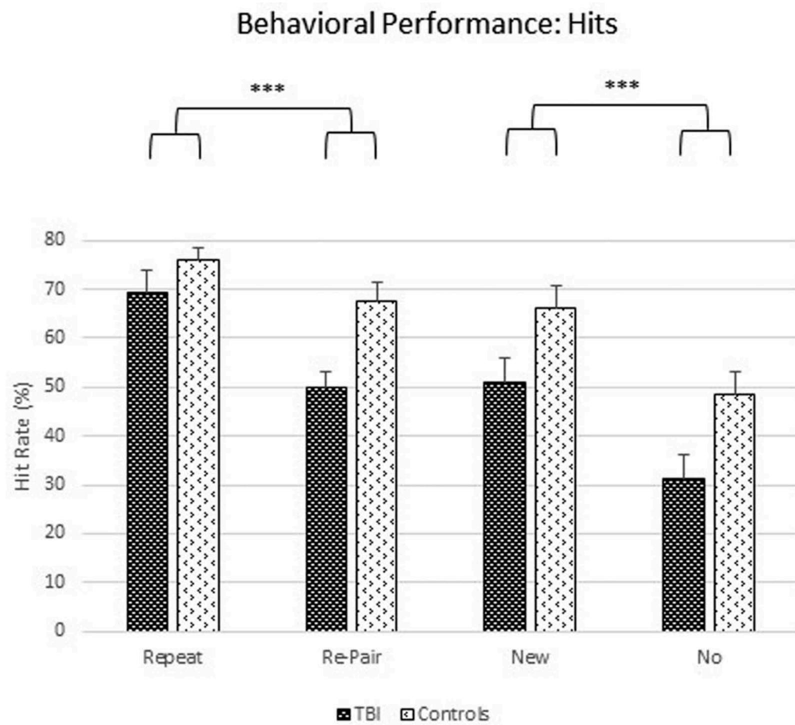

Figure 1. Percent Hit rates for the control group and the TBI group, as a function of the different context conditions.

p < 0.001, η_p^2 = 0.13 and Group main effect was marginally significant $F(1, 45)$ = 4.31, p = 0.04, η_p^2 = 0.09. The Context by Group interaction was not significant F(3, 135 = 0.48, p = 0.70, η_p^2 = 0.01. Post-hoc analysis using Bonferroni procedure was conducted in order to detect the source of the context effect. It was found that although there is a linear increase from the Repeat to the No condition (see Figure 2), only the

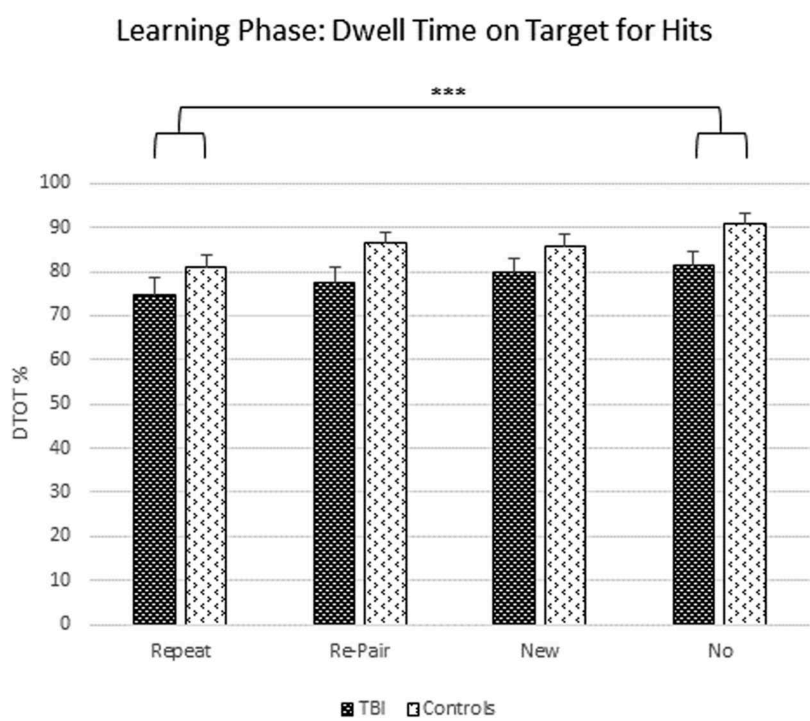

Figure 2. Correct responses for old faces (Hits) – Percent Dwell Time on target at Learning phase for the control group and the TBI group, as a function of the different context conditions.

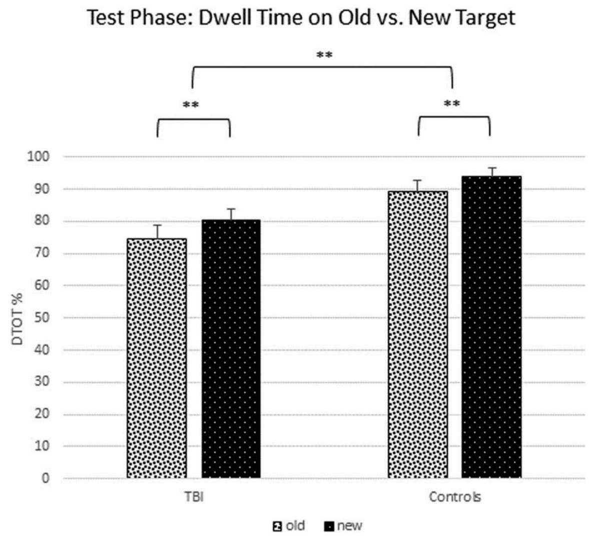

Figure 3. Old vs. New faces – Percent Dwell Time on target at Testing phase for the control group and the TBI group.

difference between these two conditions reached significance ($p < .001$). These results suggest that for a face to be correctly recognized at test in the Repeat condition required significantly less DTOT at the learning phase, compared to the No context condition which required longer DTOT for a face to be recognized.

Test stage

Next, we wanted to test the hypothesis that DTOT at test would be longer on new items than on old items (i.e., "repetition effect"). Furthermore, it was predicted that this effect would be less pronounced in the TBI group compared to controls. Thus, we compared the groups' DTOT at test on the items of the Repeat condition in which target and context are old, versus the condition in which target and context are new (TnCn). Overall, as predicted, DTOT was significantly longer on the new items than on the old items, $F(1, 45) = 9.43$, $p < 0.01$, $\eta_p^2 = 0.17$. It was also found that overall, the control group had longer DTOT than the TBI group, $F(1, 45) = 8.71$, $p < 0.01$, $\eta_p^2 = 0.16$. Contrary to our prediction, the interaction did not reach significance, $F(1, 45) = 0.25$, $p = 0.62$, $\eta_p^2 = 0.01$, indicating that both groups spent proportionally more time to the same extent on the new items than on the old items t (see Figure 3).

Discussion

The findings of the present study are consistent with previous research that tested the effect of mild-to-severe TBI on memory CE. In other words, although the overall controls' hit rate was higher than that of the TBI group, both groups benefited from reinstatement of the original context (i.e., CE) to the same extent (Vakil et al., 1994, 1991, 1996, 1997). Previous studies have demonstrated that CE is composed of multiple cognitive processes (Murnane et al., 1999; Vakil et al., 2007). The two most important processes are *binding/ensemble* and *familiarity*. Recognition based on binding reflects an integration of both the old target and context stimuli. In contrast, recognition based on familiarity reflects the additive effect of familiarity of both old target plus old context. As explained in the introduction, unlike previous studies with TBI, we added the Re-pair condition because the comparison between the Repeat condition (the exact target-context pair from encoding is presented at test) and Re-pair (target and context that were presented at encoding but not as a pair), enables dissociation between the binding and familiarity components of CE. The fact that both groups showed an advantage in the Repeat over the Re-pair condition which did not differ from the New condition, indicates that recognition of both groups was based primarily on binding rather than familiarity (See Figure 1).

Monitoring of eye movements provided us with some information not consciously available to participants that could shed some light on the underlying cognitive processes involved in performing the task. First, an interesting finding is that both groups followed the instruction to focus on the face at the learning phase, although the control group spent (marginally significant) more time on the face than the group with TBI. This is consistent with previous studies that reported on the effect of TBI on selective attention (Virk et al., 2015).

Furthermore, it was found that the Repeat condition (with maximal contextual cuing) needed significantly less DTOT at encoding in order to be correctly recognized, compared to the No condition (no contextual cuing) (see Figure 2). This accords with previous studies (Heisz et al., 2013; Kafkas & Montaldi, 2011) demonstrating that the duration of processing at encoding predicts later recognition memory strength. Thus, when the recognition cues are more available, less processing at encoding is required at test to be correctly recognized, as compared to when poor recognition cues are provided, correct recognition then required significantly more processing at encoding.

Analyzes of eye movements at the test phase also yielded some interesting findings. Just like at encoding, compared to the TBI group, the control group spent more time on target at test. As predicted, both groups spent more time on the new stimuli (target and context new) compared to the old stimuli (Repeat, target, and context old) (see Figure 3). This is consistent with the "repetition effect" hypothesis, according to which new stimuli draw more attention than old stimuli (Chanon & Hopfinger, 2008; Hannula et al., 2010; Ryan et al., 2007).

In summary, this study makes two significant new contributions to the literature on implications of TBI for memory. First, although overall memory for faces following TBI is impaired compared to that of controls, judging by analyzes of its components, the magnitude and pattern of CE is the same for both groups. This confirms previous studies demonstrating impaired direct memory target information (faces in the present study) while CE is preserved. The present study added to the literature the finding that the pattern of the components of the CE in TBI is similar to that of controls.

Second, analyzes of eye movements at the learning and testing phases revealed a consistant pattern, namely that the TBI group has difficulties focusing on the target information. This finding could be utilized as a memory remediation intervention strategy for individuals suffering from TBI. For example, they can be encouraged to spend more time on information to be remembered (i.e., target). Even though DTOT was lower for the TBI group compared to the control group, the pattern of eye movements of both groups was very similar. As can be seen in Figure 2, relative DTOT at encoding on the various context conditions was parallel in both groups. Similarly, as can be seen in Figure 3, at the test phase the relative DTOT on the new and old stimuli was the same for both groups. In conclusion, the eye movement findings mirror the behavioral findings. In both types of data, the overall performance of the TBI group was lower than that of controls (lower hit rate and lower DTOT), while at the same time the pattern of behavioral and eye tracking results is similar (as indicated by lack of interactions with group effect). Further research is required before claiming causal relations between eye movements and recognition.

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Disclosure statement

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Appendix A.

Example of the two polygonal AOIs “face“ (i.e., target) and ”hat” (i.e., context).

Appendix B.

Stimuli presented at the Learning phase:

Stimuli presented at the Testing phase: top four are old faces, bottom three are new faces

Repeat

Re-Pair

New

No

Old

New

No