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Research paper

Memory control ability modulates intrusive memories after analogue trauma

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ABSTRACT

Background: Most people suffer from intrusive memories in the aftermath of trauma. For survivors' well-being, it is key that these intrusions are controlled. Memory control can be exerted through retrieval suppression. Poor retrieval suppression, however, should be associated with persistent distressing intrusions and posttraumatic stress disorder (PTSD). This study tested the hypothesis that individual differences in retrieval suppression predict intrusive memories after trauma. Retrieval suppression was examined with the think/no-think task (TNT) using behavioral and event related potential (ERP) measures.
Methods: Twenty-four healthy participants watched a "traumatic" film after performing the TNT task. The frequency and distress of intrusions from the "traumatic" film was measured with an electronic diary. Additionally the Impact of Event Scale (IES) was assessed.
Results: In line with our hypothesis, behavioral measures of retrieval suppression ability predicted reduced distress ratings for intrusions ($r = -.53$, $p < .01$). Further ERP markers of retrieval suppression (a fronto-centrally distributed N2) predicted reduced distress ratings for intrusions ($r = -.45$, $p < .05$) and reduced IES Intrusion scores ($r = -.56$, $p < .01$).
Limitations: The presented film is a relatively mild stressor as compared to a real-life trauma. Further studies are needed to explore the role of memory control processes for real-life trauma.
Conclusions: Participants with lower retrieval suppression ability exhibited less distressing intrusive memories after analogue trauma. The ERP correlate of retrieval suppression was associated with less distressing intrusive memories and reduced IES Intrusion scores, suggesting that deficient memory control is a potential risk factor for developing PTSD.

1. Introduction

In the aftermath of trauma, most survivors experience intrusive memories of the traumatic event. While these memories decline for some survivors in the months after the trauma, others continuously suffer from them and develop posttraumatic stress disorder (PTSD) (Michael et al., 2005). Naturally, traumatized people quite often are highly motivated to prevent trauma memories from spontaneously coming to mind, as they wish to reduce the distress they cause. Avoiding potential reminders of the traumatic event is an essential part of the posttraumatic stress symptomatology (American Psychiatric Association, 2013). Although avoiding reminders is one means to curtail intrusions, it is not the only one. Previous research indicates that people are often able to control their memory retrieval voluntarily even when they are directly confronted with reminders, a process called retrieval suppression (Anderson and Hanslmayr, 2014; Catarino et al., 2015). However, the ability to suppress memory retrieval varies substantially across people (Levy and Anderson, 2008, 2012), and thus may offer an explanation for individual differences in PTSD symptoms. When people encounter reminders to a recent trauma, nearly everyone will experience memories intruding into their mind; but, people who have strong retrieval suppression ability can eliminate these memories from awareness, and their tendency to intrude again (Levy and Anderson, 2008). On the other hand, people with deficient retrieval suppression will not be able to accomplish this, and

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should, as a result, keep experiencing intrusive memories. Consistent with this, a recent study investigating the ability to suppress retrieval of aversive images in traumatized subjects with and without PTSD showed that retrieval suppression is compromised in PTSD patients (Catarino et al., 2015). Although this study links PTSD to retrieval suppression deficits, it cannot answer the question whether these deficits are caused by PTSD or instead constitute a risk factor for its development.

To study retrieval suppression in the laboratory, Anderson and Green (2001) developed the think/no-think (TNT) task. In this paradigm, people are repeatedly prompted with cues to previously learned memories and are asked to either retrieve the memory ("think" trials), or to stop its retrieval ("no-think" trials). Numerous studies have found that no-think items are more poorly recalled on subsequent memory tests (Anderson & Green, 2001; Anderson & Huddleston, 2011; Anderson et al., 2004), an effect termed suppression-induced forgetting. Suppression-induced forgetting has been observed for a number of neutrally and negatively valenced stimuli, including words, objects, scenes, and autobiographical memories (Anderson and Hanslmayr, 2014; Anderson and Huddleston, 2012; Catarino et al., 2015; Küpper et al., 2014). Even if the overall memory sometimes still is accessible after retrieval suppression, reductions in the specificity of autobiographical memories (Stephens et al., 2013) or the number of details remembered from visual scenes can be observed (Catarino et al., 2015; Küpper et al., 2014).

Recent neuroimaging studies found negative coupling between the right dorsolateral prefrontal cortex (DLPFC) and the hippocampus during no-think trials, indicating that a control process supported by the DLPFC down-regulates activity in the hippocampus to stop retrieval (Benoit and Anderson, 2012; Gagnepain et al., 2014). An electrophysiological correlate of this putative control process was found in a fronto-centrally distributed N2 component, a negative-going ERP component which is consistently larger during retrieval suppression than during retrieval (Bergström et al., 2009b; Bergström et al., 2007; Depue et al., 2007; Mecklinger et al., 2009; Waldhauser et al., 2012). Importantly, a larger N2 deflection during retrieval suppression predicted greater suppression-induced forgetting (Mecklinger et al., 2009). A correlation has also been demonstrated between the TNT N2 and the N2 observed in a motor stopping task (Mecklinger et al., 2009), suggesting that both processes recruit general response inhibition mechanisms. Critically, as these general control processes have been found to reduce involuntary memory retrieval in the laboratory, they may also be involved in inhibiting involuntary retrieval of traumatic memories (Benoit et al., 2014; Catarino et al., 2015; Levy and Anderson, 2012; Mecklinger et al., 2009). Thus, measuring variation in the N2 during retrieval suppression may provide an important window into individual differences in the underlying neural mechanisms that determine which people are vulnerable to persistent intrusive memories in the aftermath of trauma.

Therefore, we hypothesize that deficient retrieval suppression, as indexed by behavioral and ERP estimates, are a potential risk factor for PTSD. People who are good at retrieval suppression should also be more capable of limiting the accessibility of traumatic memories. To test this hypothesis, it is necessary to employ a prospective design that assesses retrieval suppression ability *before* a traumatic event occurs, and then examine how variation in this ability predicts response to a subsequent trauma. Such a prospective design is very difficult to realize in clinical samples. One way to circumvent this problem is to use analogue paradigms: The trauma film paradigm provides a prospective experimental tool for investigating intrusive memories in the laboratory (for a review see Holmes and Bourne, 2008). In this paradigm, healthy participants watch a film clip depicting traumatic events (e.g. a car accident or a homicide) and are asked to record their intrusive memories of the film over the following days. In a recent meta-analysis of 458 participants the mean number of intrusive memories in the week following film exposure was 5.53 ($SD=6.52$; Clark et al., 2015), indicating that this paradigm is a valuable tool for inducing intrusive memories.

To test our hypotheses we combined the TNT procedure and the trauma film paradigm. We first used the TNT procedure to estimate participants' general retrieval suppression ability with behavioral (suppression-induced forgetting) and ERP (N2) measures. Neutrally valenced word stimuli were used, as in recent studies suppression-induced forgetting effects for both behavioral and ERP estimates are reliably found for these stimuli (Anderson and Hanslmayr, 2014). After having performed the TNT, participants watched both a "traumatic" and a neutral film clip. Intrusive memories of the films were measured with an electronic diary. Additionally the Impact of Event Scale (IES), a clinical standard questionnaire assessing PTSD symptoms, was administered. To keep the simulation as natural as possible, no instruction to suppress memories of the films was given. We expected that participants with high retrieval suppression ability, as indicated by behavioral and ERP estimates, would show fewer intrusive memories from the "traumatic" film than would participants with low retrieval suppression ability (Hypothesis 1). Anderson and Hanslmayr (2014) recently argued that a strong motivation is necessary to effectively suppress a memory. In this study we did rely on the natural motivation most people have to avoid negative stimuli (e.g. Elliot, 2006) and expected participants to be especially motivated to inhibit the occurrence of those memories (or details) that are the most distressing. Therefore, we predicted that differences in retrieval suppression ability between participants would also be associated with differences in the average distress experienced during intrusions. In detail, we expected participants with low retrieval suppression ability, as indexed by behavioral and ERP measures, to show on average more distressing intrusions than participants with high retrieval suppression ability owing to their reduced ability to suppress unpleasant details or events (Hypothesis 2). Finally, we predicted that retrieval suppression ability, for both behavioral and ERP measures, would predict IES scores (Hypothesis 3).

2. Methods

2.1. Participants

Twenty-four students (12 female, age ranged from 18–32 years, $M=24.7$, $SD=4.20$) were recruited on the campus of Saarland University and participated in exchange for 76 Euro. All participants had normal or corrected-to-normal vision, were native German speakers, right-handed, and gave informed consent. Participants were interviewed to exclude any history of neurological or psychiatric disorder or prior exposure to a traumatic event. The research was approved by the Department of Psychology Ethics Committee of Saarland University. The electroencephalogram (EEG) data of three participants were excluded due to recording errors.[1]

2.2. Think/no-think task

Eighty-four weakly related, neutrally valenced word pairs were

[1] All statistical analyses of behavioral data showed the same pattern of results for the complete and the reduced dataset without the three excluded participants. Behavioral results are reported for the complete sample.

composed (60 critical items and 24 filler items). Words were selected from a German standardized data base (Melinger and Weber, 2006). Each word pair comprised a cue (left hand) and a response (right hand) word and was presented in the center of a 100 Hz computer display on white background, using E-Prime 2.0 software (Psychology Software Tools Inc., Sharpsburg, USA). The critical pairs were rotated across experimental conditions (baseline, think, no-think) and across subjects.

The TNT task consisted of four phases (Anderson and Green, 2001; Benoit and Anderson, 2012): Training, Practice, Think/No-Think, and Final Recall. The Training phase had three stages. First, each word pair was presented for 3400 ms (ISI: 600 ms). Second, participants overtly recalled the response to the cues, which were shown for up to 4000 ms, or until response. Following a 600 ms ISI, the correct response appeared for 1000 ms. This procedure was repeated until participants recalled at least 50% of the critical responses. Third, we presented each cue one more time for up to 3300 ms (ISI: 1100 ms) to assess which responses had been learned.

During practice, all participants were trained on the TNT task, using filler items. They were instructed to covertly recall the responses for cues presented in green (think condition), but to block out all thoughts of the associated responses for cues presented in red (no-think condition). Moreover, participants were instructed to not try to generate distracting thoughts in order to not think about the No-Think items but rather to control memory by suppressing retrieval (known as a “direct suppression” instruction) (see Benoit and Anderson (2012), Bergström et al. (2009a) and LeMoult et al. (2010)). Think and no-think trials alternated pseudo-randomly. Each cue was on screen for 3000 ms (ISI: 1000 ms) – timings identical to the actual TNT phase. After the first half of the Practice phase a questionnaire was administered verbally to help identify any covert rehearsal of no-think items and allow the experimenter to give feedback to correct this problem (Bulevich et al., 2006).

After practice, the critical TNT phase was split into five blocks. In each block, participants saw each cue of the think and no-think pairs twice. Within a block, a given cue was only repeated once all other cues had been presented. Thus, each critical item was retrieved or suppressed ten times. A short break (45 s) separated each block. After the second block the above mentioned questionnaire was administered again.

In the final test phase, participants were given cue words and asked to recall the associated response words – irrespective of prior instructions. The cues were presented for up to 3300 ms (ISI: 1100 ms). Cues were presented in block randomized format, with each block of 6 trials containing two items from each of the Think, No-think, and Baseline conditions, presented in random order.

2.3. Analogue trauma

All participants saw two film clips (one neutral, one “traumatic”) in pseudo-randomized order. The neutral film consisted of scenes (11 min) from the movie *Three Colors: Blue* directed by Krzysztof Kieslowski (1993) (Schaefer et al., 2010). The “traumatic” film consisted of scenes (11 min) from the movie *Irreversible* by Gaspar Noé (2002) (Nixon et al., 2007; Qin et al., 2009; Verwoerd et al., 2010). After watching each film clip, an adapted version of the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988) was administered, assessing how participants felt while watching the preceding film. Thereafter, participants were asked to rate how strongly each film caused physiological arousal on a 5-point scale going from “very slightly or not at all” to “extremely.”

2.4. Assessment of intrusive film memories and the Impact of Event Scale

During the five days following film presentation, participants documented every intrusive film memory, using an iPod Touch (4th gen., Apple Inc., Cupertino, USA) running Forms VI (Pendragon Software Corporation, Chicago, USA). Participants were instructed to carry along the mobile device during the whole assessment period and register every intrusive memory immediately after its occurrence. Intrusions were defined as spontaneous involuntary memories that could include thoughts, pictures, noises, and emotions. Every morning and evening participants were prompted to enter up all intrusive memories they have forgotten to enter. For each intrusion, participants rated how distressing it was on a 10-point scale going from “not at all” to “extremely”. These ratings were averaged to determine the mean distressingness.

Six days after film presentation, every participant completed the Impact of Event Scale (IES-R; German translation; Maercker and Schützwohl, 1998; Weiss et al., 2004), a 22-item questionnaire assessing PTSD symptoms, with regard to the “traumatic” film. Every item (e.g. “Things I saw or heard suddenly reminded me of it”) was rated on a 5-point scale spanning from “not at all” to “extremely”.

2.5. Procedure

Participants were run individually. On the first day, they were interviewed to exclude any axis I disorder (5th ed.; DSM-V; American Psychiatric Association, 2013) or prior traumatic experience. Participants then completed an Operation Span task (Conway et al., 2005; Unsworth et al., 2005), the Thought Control Questionnaire (Reynolds and Wells, 1999) and the Viennese Matrices test (Formann et al., 2011). Data of these tests will be reported elsewhere. The following day, participants performed the TNT task. During this task EEG was recorded. On the third day, participants watched the two films. Intrusions were documented over the following five days. Six days after film presentation participants completed the IES and were fully debriefed.

2.6. Statistical analysis of behavioral measures

Performance data of the TNT task was analyzed using a mixed-design analysis of variance (ANOVA), with response condition (think, no-think, baseline) as within-subject factor and counterbalancing of items through each condition (three levels) as between-subject factor. To assess individual differences, a score for each participant's retrieval suppression ability was calculated by subtracting recall of no-think items from baseline items. Thus, participants with higher retrieval suppression ability had higher scores. This measure was z-normalized within that participant's counterbalancing group to control for differences in the memorability between items (see Anderson et al. (2004) and Levy and Anderson (2012)).

To determine whether participants experienced more negative emotions and subjective arousal during the “traumatic” film as compared to the neutral film and whether they had more intrusive memories of the “traumatic” as compared to the neutral film individual within-subject t-tests were calculated.

Correlation analyses focused on the association between behavioral and ERP estimates of retrieval suppression in the TNT task and intrusion measures (i.e. intrusions frequency and distress in the electronic diaries and the IES subscales). Pearson correlations were calculated.

2.7. Electrophysiological recording, preprocessing, and ERP statistical analysis

Subjects were seated in an electrically shielded room. While performing the TNT task, the electroencephalogram (EEG) was continually recorded from the scalp using a 72-channel active-electrode system (Biosemi Inc., Amsterdam, The Netherlands) with 64 standard 10–20 electrode positions, 6 EOG channels (2 × VEOG, 1 × HEOG, 1 × REOG as the average of all 6 channels referenced to averaged mastoids) and 2 mastoid reference channels. Detailed information on electrophysiological recording and preprocessing can be found in Supplementary Information. ERP waveforms for think and no-think trials were quantified by measuring the mean amplitudes in two time windows (180–240 ms, 350–450 ms). Selection of these time windows was based on visual inspection and previous ERP research (Mecklinger et al., 2009). Statistical analysis of the ERP data was based on the following electrodes: frontal (F3, Fz, F4), central (C3, Cz, C4), parietal (P3, Pz, P4). To quantify individual differences, ERPs to no-think items were subtracted from ERPs to think items. Thus, subjects with higher negativity for no-think items, had numerically larger scores. These measures were z-normalized within each counterbalancing condition. Scores from FCz recording site were used for the correlational analyses, as the ERP subtraction measures in both time windows were largest at this recording site.

3. Results

3.1. Suppression-induced forgetting was observed

We found significant suppression-induced forgetting effects in the TNT task, as no-think items were more poorly recalled than were baseline items (Fig. 1; $F(1, 21)=7.16$, $p=.01$, $\eta_p^2=.254$). This indicates that participants were able to suppress memory retrieval successfully, which led to reduced recall rates. No-think recall was also lower than think recall ($F(1, 21)=12.60$, $p=.002$, $\eta_p^2=.375$). No significant difference was found between think and baseline recall ($F(1, 21)=0.34$, $p=.57$, $\eta_p^2=.033$).[2] As the baseline recall rate was relatively high, this may be due to ceiling effects.

3.2. Both enhanced early negativity and N2 components during retrieval suppression predicted later suppression-induced forgetting

Grand average ERPs revealed pronounced differences between the think and no-think conditions (Fig. 2A). The first ERP effect consisted of an early negativity (~200 ms) that was larger in the no-think condition than in the think condition. As apparent from Fig. 2B, the early negativity to no-think trials had a broad bilateral distribution and co-occurred with a positive (P2) deflection to think trials. The largest differences between think and no-think trials emerged at frontal and central sites (Bergström et al., 2009a; Mecklinger et al., 2009; for similar results). The early negativity was followed by a second negative going component with a similar fronto-central maximum that peaked around 400 ms. As it resembled the N2 component related to motor stopping in previous studies (Mecklinger et al., 2009), it will be referred to as the N2 effect in the following. Notably, the N2 was larger for no-think than for think trials, indicating that it reflects a process relevant for retrieval suppression.[3]

In a complementary analysis, we explored whether the early negativity and the N2 predicted individual differences in retrieval suppression. The early negativity was positively correlated with

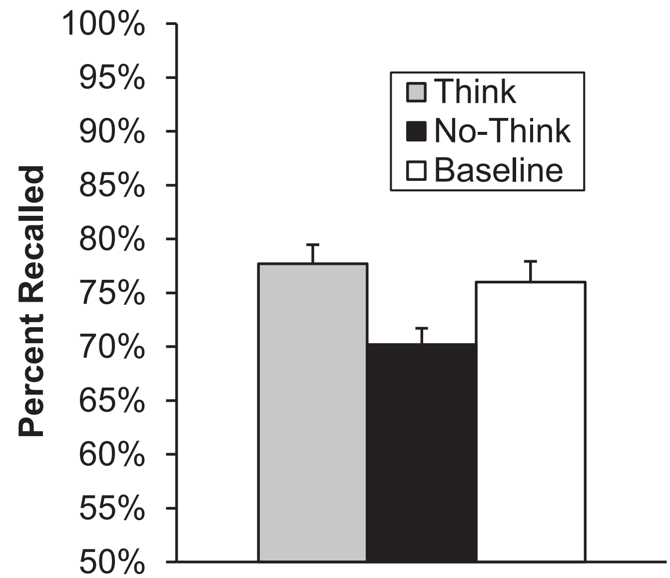

Fig. 1. Cued recall rates for previously learned word pairs. Recall was reduced in the no-think condition compared to the baseline condition and the think condition. The error bars represent the standard error following Cousineau-Morey corrections for within-subject designs (Cousineau, 2005; O'Brien and Cousineau, 2014).

suppression-induced forgetting at the level of individual participants. The larger the amplitude differences of the early negativity between the think and no-think conditions the larger suppression-induced forgetting scores ($r(19)=.57$, $p=.007$). The same correlation pattern was obtained for the N2 difference measure ($r(19)=.48$, $p=.03$; Fig. 3A), indicating that both ERP components may reflect processes relevant for suppression-induced forgetting.

3.3. The aversive film led to emotional reactions and intrusive memories

Participants reported significantly more negative emotions and higher physiological arousal during presentation of the "traumatic" film compared to the neutral film (negative emotions: $t(23)=11.36$, $p=.001$, $d=2.32$; arousal: ($t(23)=12.60$, $p=.001$, $d=2.57$).

Furthermore, participants reported between 1 and 10 intrusive memories of the "traumatic" film ($M=4.0$, $SD=2.9$), while the number of intrusions of the neutral film was between 0 and 1 ($M=0.2$, $SD=0.4$). Thus, significantly more intrusive memories of the "traumatic" film than of the neutral film were reported ($t(23)=6.74$, $p=.001$, $d=1.89$). This indicates that the "traumatic" film successfully induced intrusive memories, while the neutral film did not.

3.4. Better retrieval suppression ability predicted lower intrusion distress and IES subscales

In line with our hypothesis, increased suppression-induced forgetting predicted reduced distress for intrusive memories in the electronic diary ($r(24)=-.53$, $p=.008$; Fig. 3B). However, there was no correlation between suppression-induced forgetting and overall intrusion frequency ($r(24)=.14$, $p=.52$) or IES subscales (Intrusion: $r(24)=-.17$, $p=.42$, Avoidance: $r(24)=-.18$, $p=.40$, Hyperarousal: $r(24)=-.27$, $p=.21$; Fig. 3C).

Paralleling the analysis of behavioral indices, we examined whether the N2, which in the present and in previous studies (Mecklinger et al., 2009) has been related to behavioral measures of retrieval suppression, predicted intrusion distress and frequency. Indeed, an enhanced N2 to no-think items significantly

[2] The two-way ANOVA with Response Condition (think, no-think, baseline) as within-subject factor and counterbalancing of items through each condition (three levels) as between-subject factor revealed a main effect of Response Condition ($F(2, 42)=5.34$, $p=.009$, $\eta_p^2=.203$). No main effect for counterbalancing of items was observed ($F(2, 21)=1.08$, $p=.36$, $\eta_p^2=.093$). Also no significant interaction between the two factors was observed ($F(4, 42)=1.71$, $p=.17$, $\eta_p^2=.151$).

[3] Further analyses of the ERP results are provided in the Supplementary information.

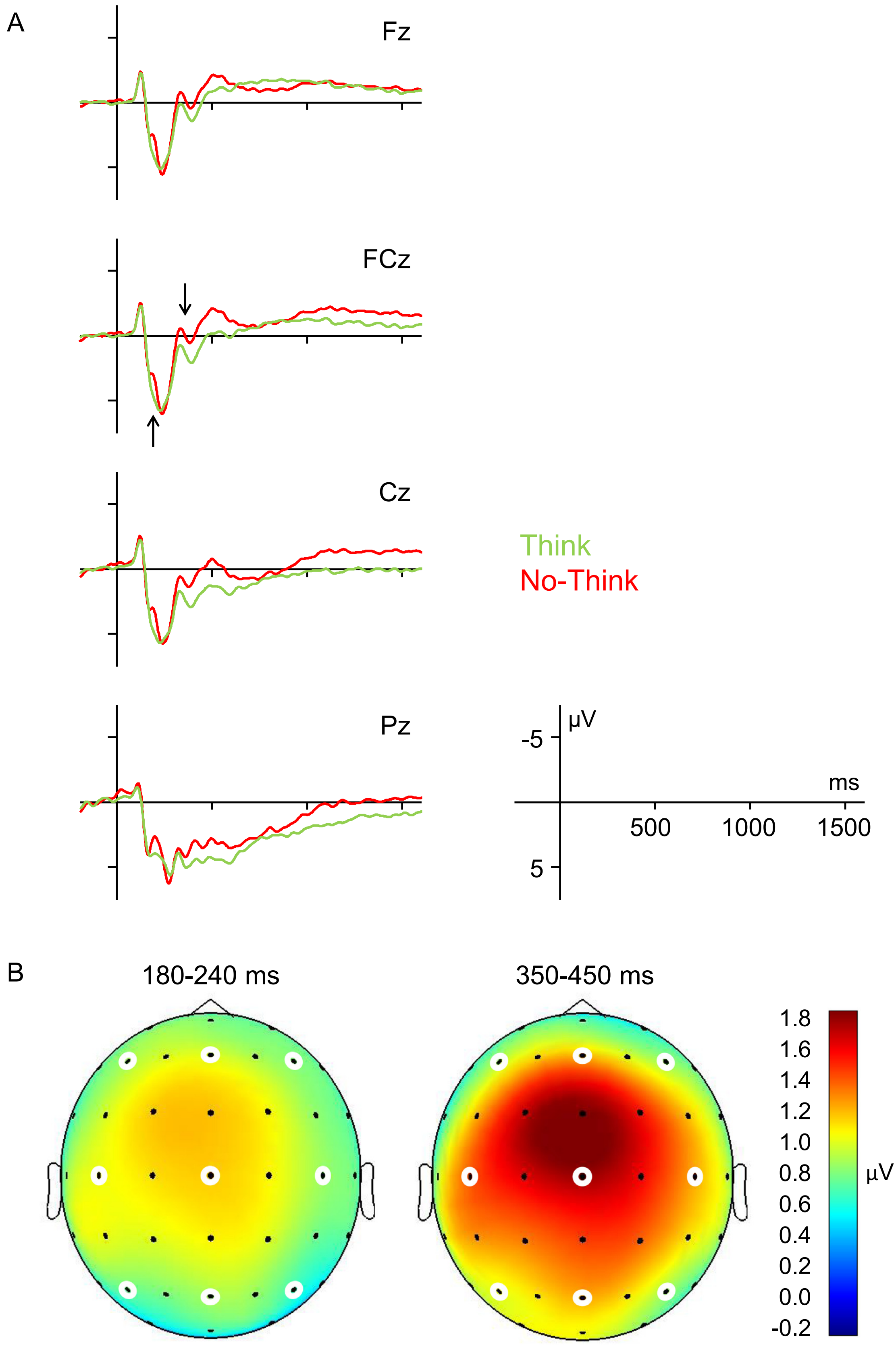

Fig. 2. (A) Grand average ERPs for the think and no-think condition during the think/no-think phase for all word pairs depicted at the Fz, FCz, Cz, and Pz recording sites. Arrows illustrate the early negativity and the N2 components. (B) Topographic maps showing the scalp distributions of the ERP differences between think and no-think Items. Grand average difference waves were computed by subtracting the no-think condition from the think condition. The electrodes used for statistical analyses are highlighted in white.

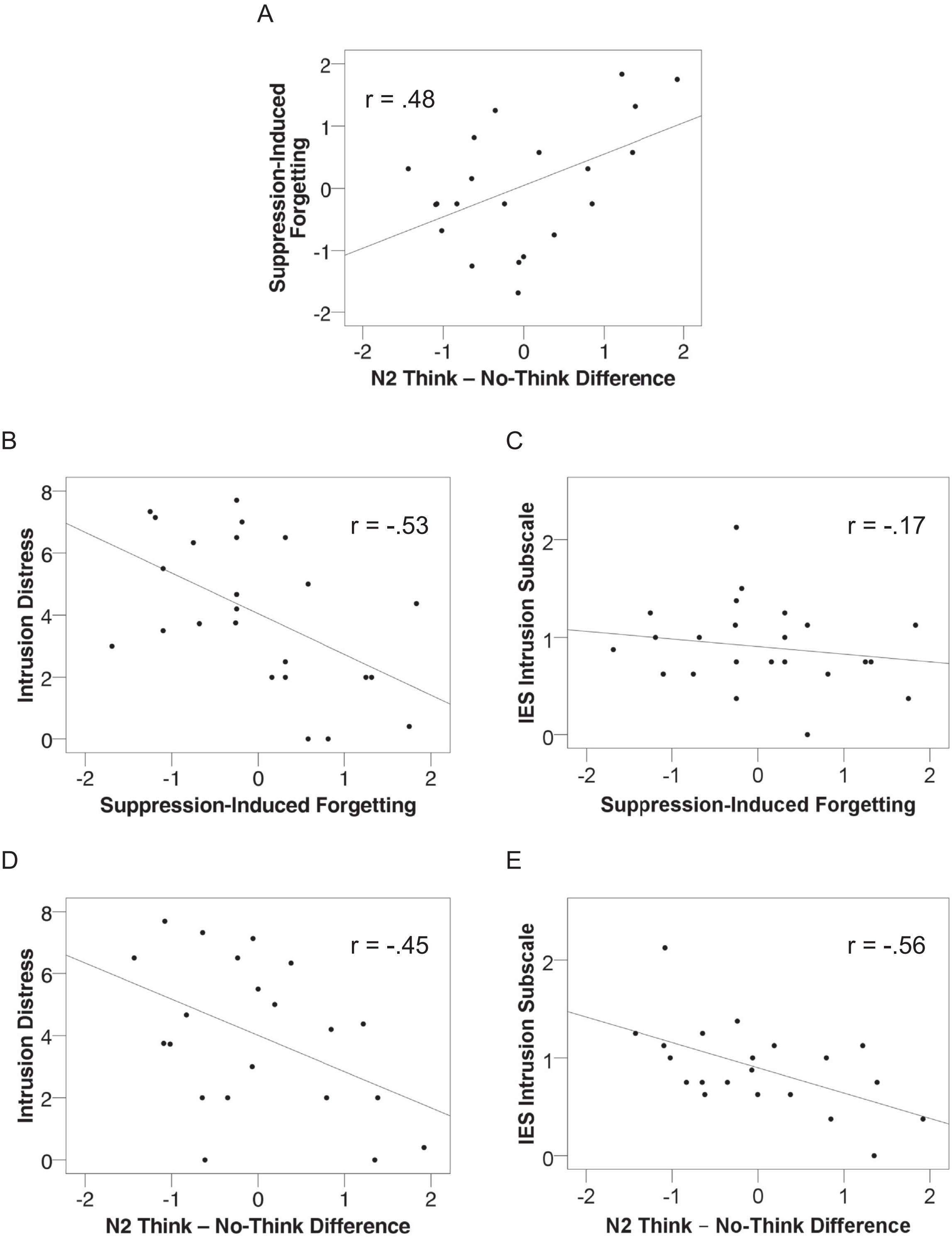

Fig. 3. (A) The positive correlation between suppression-induced forgetting (baseline recall – no-think recall) and the N2 difference (N2 think – N2 no-think). (B) The negative correlation between suppression-induced forgetting and distress ratings for intrusive memories measured by the electronic diary. (C) The non-significant correlation between suppression-induced forgetting and the Intrusion subscale of the Impact of Event Scale (IES). (D) The negative correlation between the N2 difference and distress ratings for intrusive memories measured by the electronic diary. (E) The negative correlation between the N2 difference and Intrusion subscale of the IES. All ERP measures for the correlational analyses were taken from the FCz recording site.

predicted reduced intrusion distress ($r(21)=-.45$, $p=.04$; Fig. 3D) and reduced IES subscales (Intrusion: $r(21)=-.56$, $p=.008$, Avoidance: $r(21)=-.46$, $p=.04$, Hyperarousal: $r(21)=-.49$, $p=.02$; Fig. 3E). As for the behavioral data, there was no significant correlation between the N2 and overall intrusion frequency ($r(21)=.08$, $p=.74$).

4. Discussion

Most people experience intrusive memories in the aftermath of traumatic events. While intrusive memories decline for some trauma survivors, others continuously suffer from them. In the present study, we investigated whether deficits in the ability to suppress memory retrieval are a potential risk factor for persisting intrusions. In particular, we examined whether behavioral and ERP measures of retrieval suppression ability predicted individual differences in intrusive memories as indexed by ambulatory assessment and Impact of Event Scale Intrusion subscales after an analogue trauma. In line with our hypotheses, we found that behavioral and ERP correlates of retrieval suppression ability predicted the distress caused by intrusive memories of a "traumatic" film[4]. In detail, participants with low retrieval suppression ability reported more distress during intrusive memories than did participants with high retrieval suppression ability. Furthermore, individual differences in the N2, the ERP correlates of retrieval suppression, predicted higher IES Intrusion Scores. Thus, our results are in line with previous findings linking PTSD with retrieval suppression deficits (Catarino et al., 2015) and memory control deficits (Zwissler et al., 2012). Extending these findings, our study is the first to show this relationship in a prospective design, indicating that deficits in memory control ability are a potential risk factor for developing PTSD.

Replicating earlier findings, retrieval suppression in the TNT task was reflected by greater negative going ERPs at fronto-central electrode sites. The first ERP difference between think and no-think trials emerged in the time window from 180–240 ms. This finding is in line with previous studies on retrieval suppression that observed a similar early ERP difference between think and no-think trials (Mecklinger et al., 2009; Waldhauser et al., 2012). As proposed by Bergström et al. (2009a) this early effect may reflect the detection of the need to control memory retrieval. A possible neural generator of this component lies in the frontal lobe, including the right inferior-frontal gyrus, as indicated by a dipole source localization study (Chen et al., 2012). Notably, in this study, differences in this time window predicted suppression-induced forgetting, meaning that the differential processing of think and no-think trials in this time window may be relevant for the effectiveness of retrieval suppression.

We further found an N2 component between 350 and 450 ms over frontal and central electrodes that was enhanced for no-think items compared to think items. Replicating earlier findings (Mecklinger et al., 2009), differences between think and no-think items in this time window predicted later suppression-induced forgetting. Our results indicate that this ERP component reflects processes related to the active suppression of memory traces. The early negativity and the N2 may index different component processes of inhibitory control, such as detecting the need for cognitive control and the active suppression of unwanted memories. (Bergström et al., 2009a, 2009b; Mecklinger et al., 2009; Waldhauser et al., 2012).

Building on previous research linking the N2 with retrieval suppression and motor suppression (Mecklinger et al., 2009), we wanted to examine whether this ERP component is also relevant for controlling intrusive memories of the "traumatic" film. Indeed, an enhanced N2 was related to less distressing intrusive memories and reduced IES Intrusion Scores. This indicates that the processes relevant for suppressing retrieval of simple word pairs in laboratory settings, as reflected by the N2 component in the TNT task, may also be involved in controlling unwanted memories after a traumatic experience, leading to less intrusive reexperiencing symptoms. Our results are in line with the view that retrieval suppression in both situations relies on the same mechanisms (Anderson and Hanslmayr, 2014; Anderson et al., 2004; Catarino et al., 2015; Depue et al., 2007; Küpper et al., 2014). Additionally, we found an enhanced N2 to be also correlated with reduced IES Avoidance and Hyperarousal subscales. This finding is especially interesting as it affirms the distinction we and others (Catarino et al., 2015) have made between avoidance of potential trauma reminders and the ability to suppress memory retrieval when confronted with such a reminder. Thus, participants with a reduced ability to suppress memory retrieval may tend to avoid trauma reminders, as they are less able to control their automatic memory retrieval, when confronted with such reminders. However, although the pattern of correlations with the behavioral index of retrieval-suppression ability were in the same direction, they were not reliable. Although the reasons for this are unclear, it is possible that the N2 is a more sensitive index of the underlying inhibitory control process than the behavioral correlate.

Surprisingly, we did not find a relationship between the reported overall frequency of intrusive memories of the "traumatic" film and retrieval suppression in the TNT task. Wessel et al. (2008) similarly did not find a relationship between retrieval suppression in the TNT paradigm and intrusion frequency after a "traumatic" film. These findings are in contrast to previous findings linking successful retrieval suppression with a decline of intrusions of the associated responses during the TNT task (Benoit et al., 2014; Levy & Anderson, 2012). One explanation for the missing association between retrieval suppression and intrusion frequency in this study relates to motivational issues: In order to keep the trauma simulation as natural as possible, no instruction to suppress memories of the films was given, making the engagement of suppression uncertain. Anderson and Hanslmayr (2014) recently argued that to effectively suppress a memory, it is necessary to have a strong motivation to do so. In the laboratory this motivation is achieved by experimental instructions. In the trauma film procedure, participants may only have suppressed those intrusions from the "traumatic" film that were truly distressing to them, restricting the pool of intrusions that would have been targets of active inhibitory control. This may have reduced the ability to measure the effects of suppression on overall intrusion frequency. If these lines of reasoning were correct, then limiting the analysis to only those intrusions that were highly distressing should reveal a greater reduction in intrusion frequency for people with good retrieval suppression ability compared to poor ability. Consistent with this, in a median split analysis, participants with high suppression-induced forgetting scores had a significantly reduced frequency of highly distressing intrusions (distress rating of 6–10) compared to participants with low suppression-induced forgetting scores ($t(22)=1.95$, $p=.03$ (1-sided), $d=0.83$). A second explanation for the missing association is that retrieval suppression after the "traumatic" film may have primarily reduced the distressingness of memories by degrading access to upsetting details, leaving overall access to the memories intact. Indeed, Küpper et al. (2014) found that in a pictorial TNT task memory for details of upsetting images was reduced very effectively after no-think trials, even when the image itself could be recalled (see also Noreen and MacLeod (2013) and Stephens et al. (2013)). Similarly, in this study, even though overall intrusion frequencies did not reliably decline, effective suppression of upsetting details may have reduced distress of the intrusive memories of the "traumatic" film. Whatever the explanation, our results are in line with previous research linking deficits in executive functioning (under which inhibitory control processes can be subsumed) to the regulation of negative emotions and distress (Williams et al., 2009; Williams and Thayer, 2009).

Considering that avoiding potential reminders of a traumatic event is an essential part of PTSD symptomatology (American Psychiatric Association, 2013) at first glance it may seem that promoting retrieval suppression as beneficial is inconsistent with

[4] As differential emotional reactivity to the "traumatic" film may have influenced the differential distress reactions to intrusive memories, we did control for this factor in a post-hoc analysis. When we control emotional reaction to the "traumatic" film (negative affect scale of the PANAS) on the reported relationships, the pattern of results remained the same.

clinical knowledge. However, avoiding trauma reminders may be a strategy that is mainly applied by trauma survivors that are less able to control their memory retrieval when they are confronted with such reminders. In line with this account, we found first evidence for this connection as we observed a negative correlation between the neural correlate of retrieval suppression and avoidance symptoms. Future research is needed to evaluate this speculation.

5. Limitations

The presented "traumatic" film was a relatively mild stressor as compared to a real-life trauma, thus, whether the results can be generalized to real-life traumatic experiences is not clear. Even though participants were interviewed to exclude any history of neurological or psychiatric disorder or prior exposure to a traumatic event, no standardized structured clinical interview (e.g. Wittchen et al., 1997) was conducted. Even though we expected correlations between retrieval suppression and the overall frequency of ambulatory intrusions, we did not find evidence for this relationship. However, as discussed above, we observed reduced frequencies of truly distressing intrusions in participants with high retrieval suppression ability. Furthermore, a number of variables that were not assessed in this study may have influenced our results. As previous findings suggest that retrieval suppression is associated with reduced rumination (Dieler et al., 2014; Fawcett et al., 2015; Hertel and Gerstle, 2003) on the one side and higher self-rated thought control-ability on the other side (Catarino et al., 2015; Küpper et al., 2014), differences in these variables may be confounded with our outcome variables. Furthermore, trait differences in anxiety or depression could have influenced our results. Unfortunately, we did not assess to what extend participants tried to engage in retrieval-suppression after the "traumatic" film, thus, it remains uncertain whether individual differences in coping strategies may have affected the observed pattern of results. Individual differences in adherence were not assessed in this study but could have influenced the present results.

6. Conclusions

In summary, the present findings suggest that deficient retrieval suppression is a potential risk factor for the development of distressing intrusive memories after traumatic events. People with good retrieval suppression abilities had less distressing intrusive memories of the "traumatic" film. As such, the present data support the idea that prospectively measuring poor retrieval suppression may help to identify people unlikely to recover on their own after a traumatic event and to guide appropriate intervention approaches to prevent them from developing PTSD (Dunn et al., 2009; Joormann et al., 2005; Peterson et al., 2009). Indeed, if retrieval-suppression is a general ability, as indicated here, it suggests that training this process may be a promising method for improving people's ability to cope with intrusive memories in the aftermath of trauma.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jad.2015.12.032.

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