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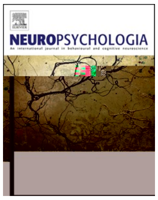

Can’t stop thinking: The role of cognitive control in suppression-induced forgetting

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ABSTRACT

The ability to control unwanted memories is essential for emotional regulation and maintaining mental health. Previous evidence indicates that suppressing retrieval, which recruits executive control mechanisms to prevent unwanted memories entering consciousness, can cause forgetting, termed suppression-induced forgetting (SIF). Since these executive mechanisms involve multiple mental operations, we hypothesize that the efficacy of SIF may be limited by individuals’ capacity limitation of cognitive control. Here, we tested this hypothesis. Participants were assigned to two groups based on the median of their cognitive control capacity (CCC, estimated by the backward masking majority function task) and performed the think/no-think task with electrophysiological signals recorded. The results showed that the SIF effect was observed only in the high CCC group but not in the low CCC group. In accordance, repeated suppression attempts also resulted in a steeper reduction in intrusive thoughts in the high CCC group. Furthermore, ERP analysis revealed a decrease in recollection-related late parietal positivity (LPP) under the no-think condition in the high CCC group. A mediation analysis revealed that the reduced intrusive memories mediated the effect of CCC on SIF. These findings suggest that suppressing retrieval could reduce traces of the unwanted memories, making them less intrusive and harder to recall. More importantly, successful SIF is constrained by the capacity of cognitive control which may be used to ensure the coordination of multiple cognitive processes during suppression.

1. Introduction

There are some unpleasant memories that we would prefer to forget. For example, people sometimes suffer from intrusive memories after a traumatic event. To reduce the emotional distress caused by these memories, individuals need to deliberately control their memory. It has previously been proved that people often have control over their memory even when directly confronted with reminders; this is called retrieval suppression (Anderson and Hanslmayr, 2014; Catarino et al., 2015). Suppressing the retrieval of unwanted memories is considered a critical ability for mental health (Costanzi et al., 2021). But not all individuals are equally effective at suppressing retrieval (Levy & Anderson, 2008, 2012) and many studies suggest that deficits in controlling memories and thoughts are the core of some psychological disorders (Goschke, 2014; Hertel, 1997, 1998, 2007; McTeague et al., 2016). Why does the ability to suppress memory retrieval vary among people and what is the key factor determining this variation? Figuring out answers to these questions will contribute to effective management of long-term memory, the maintenance of mental wellbeing, and in particular, better intervention in those psychological disorders characterized by intrusive thoughts and memories.

Retrieval suppression in the laboratory is generally studied using the think/no-think (TNT) task (Anderson and Green, 2001). During this task, participants learn a series of cue-target pairs, such as word pairs. Then they are presented with cues from learned pairs and asked to recall the target word corresponding to the cue (think condition) or avoid recalling the target word (no-think condition). Sufficient evidence has shown that the “no-think” manipulation leads to worse recall of target words compared to the “baseline (natural decay)”; this is termed as “suppression-induced forgetting” (SIF, Anderson and Hanslmayr, 2014; Depue et al., 2007; Noreen et al., 2014; Noreen and Macleod, 2013, 2014). The SIF effect is suggested to arise from inhibitory control process

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that disrupts the availability of the unwanted memory and later renders it inaccessible (Anderson and Green, 2001; Anderson and Hanslmayr, 2014; Engen and Anderson, 2018; Meyer and Benoit, 2022). Recent neuroimaging studies showed that "no-think" effort engages brain areas related to cognitive control, i.e., the right dorsolateral prefrontal cortex (DLPFC) and the dorsal anterior cingulate cortex (dACC, Anderson et al., 2004). Increased DLPFC activation is correlated with decreased activities in the hippocampal (HC) and sensory processing regions (Anderson et al., 2016; Benoit and Anderson, 2012; Benoit et al., 2015; Depue et al., 2007; Gagnepain et al., 2017; Levy and Anderson, 2012), and this correlation can predict later forgetting (Benoit and Anderson, 2012) and involuntary memory intrusions (Benoit et al., 2015). A recent study found that the dACC dynamically modulates inhibition control according to different cognitive control demands (Anderson and Hulbert, 2021; Braver, 2012; Braver et al., 2009; Crespo García et al., 2021). On the one hand, upon seeing the reminders of unwanted memories, dACC triggers an active control to prevent them from entering the consciousness. On the other hand, dACC is engaged in detecting the emergence of unwanted content, which amplified the top-down inhibitory control through DLPFC-HC pathway, to counteract the intrusions and remove them out of the mind (Crespo García et al., 2021). Therefore, the effective retrieval avoidance and successful intrusion elimination may depend on the integrity of one's cognitive control (Mackie & Fan, 2016, 2017).

Cognitive control refers to the flexible allocation of mental resources in favor of current goals (Badre, 2008). Well-functioning cognitive control enables individuals to coordinate mental operations under conditions of uncertainty, so that important information can be selected and prioritized into consciousness (Fan, 2014; Miller, 2000). Studies have found that cognitive control correlate with many high-level cognitive processes, such as attention (Mackie et al., 2013), thinking (Zabelina and Ganis, 2018), decision making (Waskom et al., 2017), and motor inhibition (Hampshire et al., 2010). However, it is clear that there is a capacity limitation of the mental operations in cognitive control (Fan, 2014). Recently, research has made progress in directly quantifying cognitive control capacity (Fan, 2014; Wu et al., 2016). According to information theory, the capacity of a channel is the maximum transmission rate while guaranteeing accuracy (Fan, 2014). In this frame, the capacity of cognitive control can be estimated based on the relationship between the information rate of cognitive control and response accuracy through a backward masking majority function task (MFT-M) (Chen et al., 2020; Wu et al., 2016, 2019). Cognitive control capacity (CCC, in bits per second, bps) is a r those reported elsewhere (e.g., Streb et al., 2016). The independent sample *t*-test for CCC showed that the two groups were significantly different, $t\ (40) = -7.925$, $p < .001$. Participants were asked not to consume psychostimulants, drugs, or alcohol before the experimental period. This study was approved by the local Research Ethics Committee of the School of Psychological and Cognitive Sciences, Peking University.

2.2. Procedure

2.2.1. Measurement of cognitive control capacity

The CCC of each participant was measured using the MFT-M (Chen et al., 2019). In each trial (Fig. 1), five arrows were presented simultaneously in 8 possible locations after fixation of 0–500 ms. Each arrow extended 0.37° in visual angle and pointed either left or right. Eight positions were arranged in an octagon, approximately 1.5° from the fixation. Then a mask for 500 ms was displayed at each location, followed by fixation of 0–1750 ms (depend on the presentation time of arrows). The response window began with the presentation of these arrows and lasted for a maximum of 2500 ms. Participants were asked to judge the direction of the major arrows as quickly and accurately as possible while trying to ensure accuracy. For example, when three arrows pointed right and two pointed left, the correct answer should be "right". If failing to identify, they were asked to guess within the response window. Following the response was feedback for 750 ms. A fixation was displayed at the end of each trial for a variable period of 1250–1750 ms to ensure that the duration of all trials was 5000 ms in total.

The cognitive load in this task was measured as information rate and was parametrically manipulated by varying the congruency (3 levels) and the exposure time (ET, 4 levels). The ET of these arrows was 250, 500, 1000, or 2000 ms and the congruency referred to the ratio of the arrows pointing in the majority and minority directions (5:0, 4:1, or 3:2). This task consisted of 12 blocks (3 blocks for each ET) in random order. Each block comprised 36 trials with the same ET (12 trials for each congruency level). The orders of these blocks and the trials within each block were both random. A fixation was presented at the start and end for 3000 ms. This task took 40 min with 432 trials in total and was run on a PC using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). The CCC of each participant was estimated using model fitting based on the level of cognitive load and response accuracy. Details about these can be found in a previous study (Wu et al., 2016, see https://github.com/TingtingWu222/CCC for the E-prime program of the MFT-M and Matlab scripts for the CCC estimation).

2.2.2. Think/no-think task (TNT)

Following the MFT-M task, participants performed the TNT task. The stimuli consisted of 60 semantically weakly-related two-character Chinese word pairs (e.g., "PORT-SURFACE") and 16 additional two-character words. The selection of words was based on the literature (Zhu et al., 2016). Forty-eight word pairs were randomly assigned into three equal sets for different conditions (think, no-think, and baseline), and 12 word pairs were used as stimuli for practice. The assignment of word sets was counterbalanced across experimental conditions and across participants. Word frequency, number of strokes, and familiarity were matched between word-pair sets. The 16 single words were used as filling stimuli for the EEG experiment during the TNT task.

The TNT task consisted of three phases (learning, TNT task, and test). The learning phase was divided into three sub-phases (presentation, test-feedback, and criterion test). Among the three phases, EEG signals were only recorded in the TNT phase. During all phases, the presentation of the stimulus was preceded by a fixed cross on a black screen for 1000 ms. The presentation of experimental stimuli and the recording of participants' responses were programmed with the Psychotoolbox software package (MatLabx association between the two words so that they could recall the right-hand word (the matching target) when given the left-hand word (the cue word) later. Besides, 16 single words were presented on the left side of the screen sequentially, as filling stimuli in the TNT phase. Afterward, a test with feedback was performed. The cue word was presented for 3000 ms. Participants were asked to recall the corresponding target word once they saw the cue. They were also told to press the "N" key if they could think of the target word, or to press the "M" key if they could not think of the target or were unsure of their memory. Following a 500-ms ISI, the corresponding target word was displayed for 1000 ms. The recall test with feedback was repeated in an adaptive manner until participants reported remembering all word pairs. Finally, a criterion test without feedback was implemented. Each cue was presented for 3000 ms (ISI: 1000 ms) in random order and participants were asked to type the corresponding target word into the computer. Participants were allowed to proceed with subsequent phases if they remembered >90% of the word pairs on the criterion test.

The trial diagram of the TNT phase is illustrated in Fig. 2A. This phase was divided into 8 blocks, and the EEG signal was recorded during this phase. Each block included 48 cue words, 16 each for the Think and No-think conditions, and 16 as filling stimuli. Each cue was displayed for 3000 ms in green (think trial), in red (no-think trial), or in yellow (filler trial), in the center of the screen. When a cue was presented in green, the task was to recall the associated target word as soon as possible and keep it in mind until the cue disappeared. When a cue was presented in red, the task was to avoid thinking about the associated target word while sustaining attention on the cue word until it disappeared. Moreover, participants were asked not to replace the target word with any other distracting ideas or images, but simply to stop themselves from retrieving the target. Besides, when a cue was presented in yellow, the task was to read the word and pay attention to it until it disappeared. Following each trial, participants rated the extent to which they thought of the associated target on a scale from 1 to 3 (never, briefly, often) by pressing keys. The keys were balanced between participants on the left and right hands (left: never S, briefly D, often F; right: never J, briefly K, often L). Yellow words had no associated target words, so we asked participants to report the occurrence of thoughts other than the cue. To ensure that participants have fully understood these instructions, practice with structured feedback interviews (same as Wang et al., 2019) was conducted using 12 fillers prior to the TNT phase.

In the final test phase, a surprising cue test was performed, which was the same as the criterion test in the learning phase. All previously learned cue words were presented in random order. The participants were asked to recall the corresponding target word of each cue and type it into the computer.

2.2.3. EEG recording, preprocessing, and ERP analysis

During the TNT task, EEG (Brain Products system) was recorded continuously using a 64-lead Ag/AgCl electrode cap based on the international 10–20 system (EASYCAP, GmbH, Germany). The ground electrode was between Fpz and Fz, and the reference electrode for online recording was between Fz and Cz. Eye blinks and vertical eye movements were monitored using electrodes above the right eye. The EEG traces were digitized at 500 Hz and an online band-pass filter of 0.01–100 Hz was used. The electrode resistance <5 kΩ by applying EEG paste when needed during recording.

Acquired data were preprocessed using EEGLAB 9.0 (Delorme and Makeig, 2004; Swartz Center for Computational Neurosciences, LaJolla, CA; http://sccn.ucsd.edu/eeglab), an open-source toolbox for EEG analysis in MatLab (MathWorks, Inc., Natick, MA). The offline data were re-referenced and analyzed using the average of the bilateral ear papillae (TP9, TP10) as a reference. After that, a bandpass filter of 0.05–30 Hz was applied to the offline data. Independent component analysis was used to decompose the EEG data and to correct artifacts

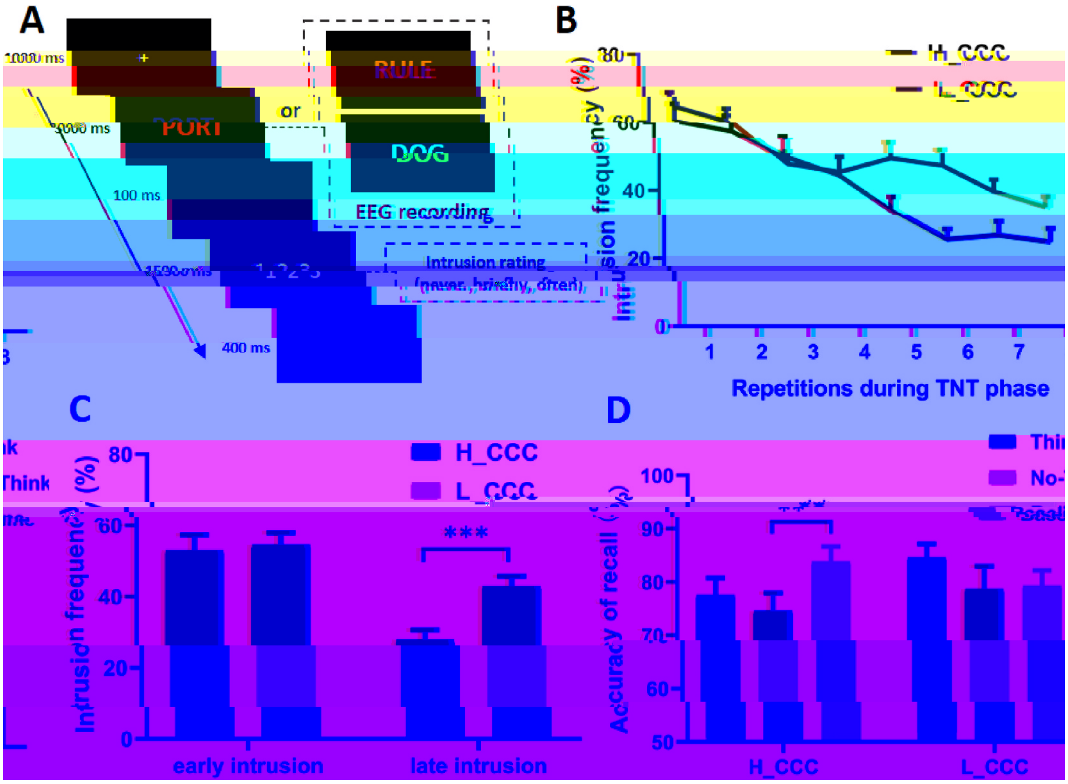

Fig. 2. Procedure and behavioral results in the TNT task. (A) Trial procedure of the TNT phase (red, no-think condition; green, think condition; yellow, filling trials. (B) Frequency of reported intrusion experiences over the 8 repetitions of think and no-think conditions in the TNT phase. (C) Frequency of reported intrusion for the early stage (first 4 repetitions) and last stage (last 4 repetitions) during the TNT phase. (D) Recall rates in the final test for participants in the high and low CCC groups. Error bars represent SEM. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

such as blinking, horizontal eye movement, ECG, and EMG. The segmentation standard took the occurrence time of the cue word as the zero point to intercept the TNT phase –500~3000 ms as the epoch, and the total length was 3500 ms. Five hundred milliseconds before the appearance of the

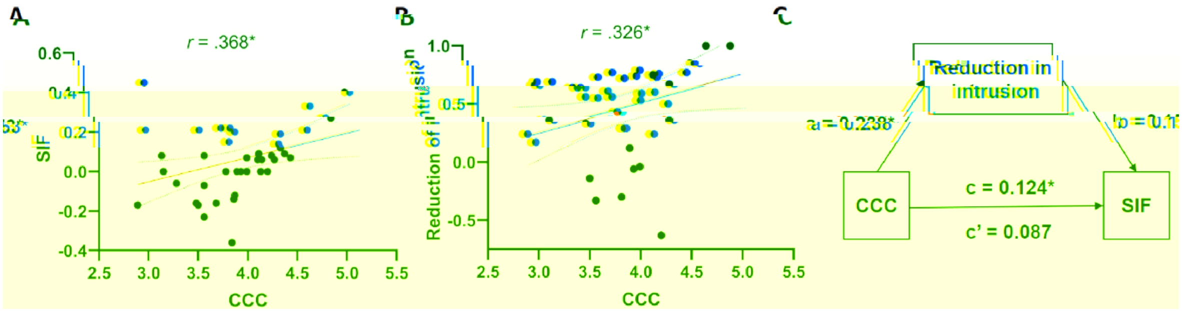

Fig. 3. (A, B) Association between cognitive control capacity (CCC) and suppression-induced forgetting (SIF) (A) and reduction in intrusion (B). (C) Mediation model for the direct and indirect effects of CCC on forgetting; reduction in intrusive memories partially mediates their relationship (*$p < .05$).

[0.420, 0.857], $p < .001$). These findings suggested that a higher CCC could predict both a larger reduction in memory intrusion during repeated retrieval inhibition attempts and a greater final suppression-induced forgetting. The greater reduction in memory intrusion, in turn, further predicted SIF.

To examine whether the effect of CCC on forgetting is mediated by a decline in intrusion, we used a bootstrapping procedure on the participants' data to compute the 95% CI around the indirect effect (i.e., the path through the mediator) using the PROCESS macro in SPSS (Model 4; Hayes, 2013). We conducted a test of indirect effects for all participants, with CCC as the independent variable, SIF as the outcome variable, and the decline in intrusion as the mediator variable (see Fig. 3C). The path from CCC to the decline in intrusion was significant (a = 0.238 [0.028, 0.408], $p = .035$), as was the path from the decline in intrusion to SIF (b = 0.153 [0.030, 0.314], $p = .030$). In addition, the results of mediation analyses showed that reduction in intrusion mediated the relationship

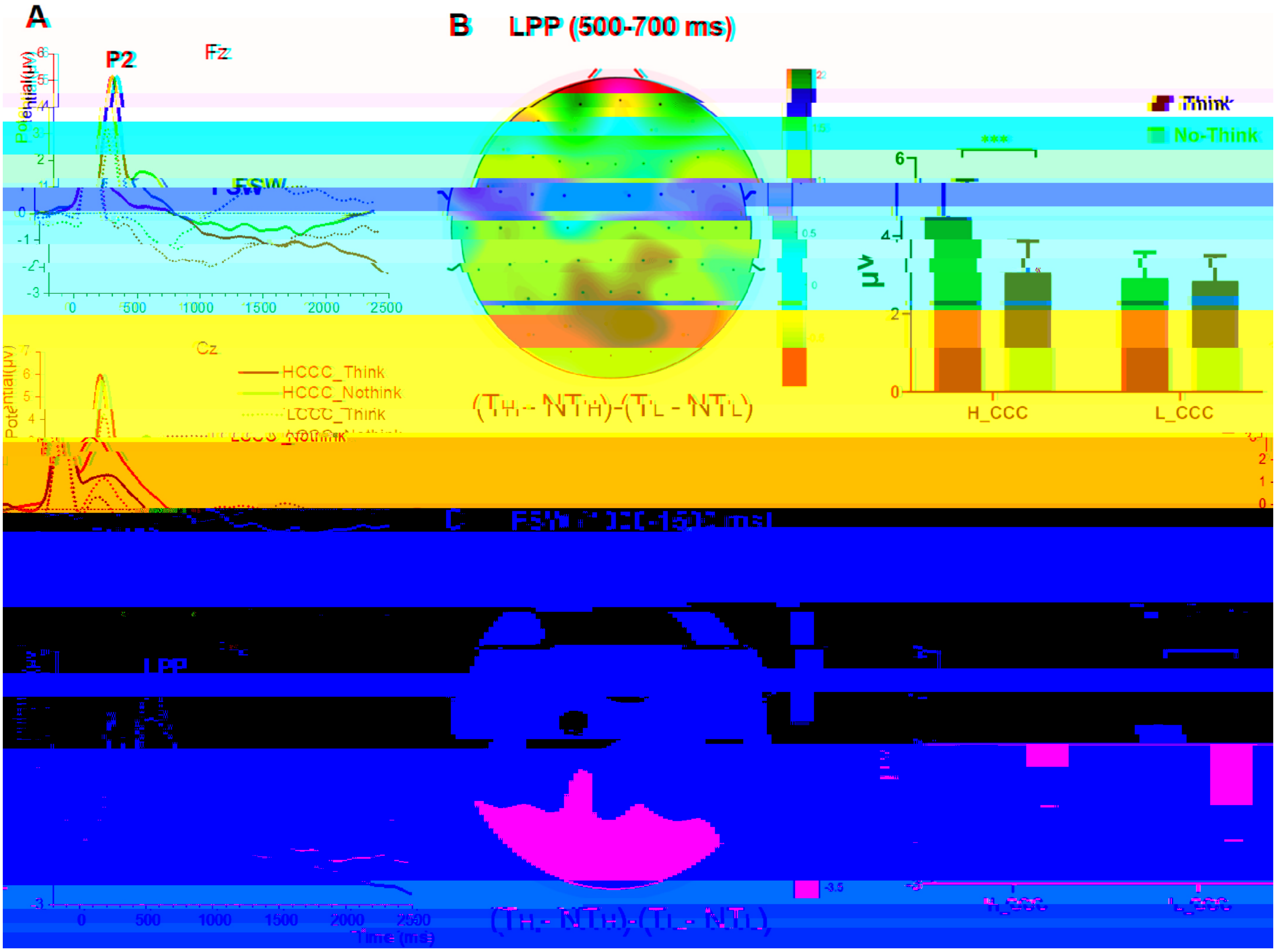

Fig. 4. ERP results. (A) Grand average ERPs from the Think/no-think phase of two groups from three electrode sites (FZ, Cz, and Pz). HCCC, high CCC group; LCCC, low CCC group. (B) Topographical map of the Group × Condition interaction of late parietal positivity (LPP) and mean LPP amplitudes for different conditions and different groups. (C) Topographical map of Group × Condition interaction of frontal negative slow wave (FSW) and mean FSW amplitudes for different conditions and different groups (T: think condition; NT: no-think condition; H: high CCC group; L: low CCC group).

between CCC and SIF (total effect: c = 0.124 [0.024, 0.224], $p = .017$; direct effect: c' = 0.087 [-0.014, 0.188], $p = .088$; indirect effect: a × b = 0.037 [0.0007, 0.093], $p = .024$). These results suggested that the decline in intrusion partially mediated the effect of CCC on SIF.

3.2. ERP results

The grand average of ERPs for the think (high and low CCC) and no-think (high and low CCC) conditions are shown in Fig. 4A. Firstly, negative FN400 effect emerged during the 350–450 ms window. Inconsistent with previous studies (Mecklinger et al., 2009), the main effect of condition was not significant, $F(1, 40) = 0.030$, $p = .863$, $\eta_p^2 = 0.001$; and the main effect of Group was not significant, $F(1, 40) = 2.172$, $p = .148$, $\eta_p^2 = 0.051$. Thus, an FN400 occurred in both groups and both conditions when the cue was presented.

Then, an LPP effect for recollection emerged during the 500–700 ms window (Fig. 4A). Analysis of the LPP revealed a significant Group × Condition interaction, $F(1, 40) = 6.908$, $p = .012$, $\eta_p^2 = 0.147$. Further pairwise comparison showed that, for the high CCC group, the LPP of the no-think was much lower than that of the think condition, $MD = -1.422$, $p < .001$ (Fig. 4B); however, in the low CCC group, the difference of conditions was not significant, $MD = -.367$, $p = .872$. Our results showed that the no-think condition has a reduced LPP amplitude compared to the think condition, but only in the high CCC group. No significant main effects were found ($ps > .05$). What's more, to check if the LPP reflected the level of recollection, we calculated the correlation between reduced LPP (think minus no-think) and the decline in intrusion and it was significant ($r = 0.437$ [0.122, 0.697], $p = .004$). The results revealed a

(Lopez-Caneda et al., 2019), these findings may suggest that people with high CCC performed better in avoiding retrieval and preventing unwanted memories entering consciousness. Moreover, being aware of intrusive memory meaned that the memory was reactivated at least briefly during the trial. The correlation between the reduced LPP effect and the reduced intrusion may indicate the consistency between the level of oral reported memory reactivation and the neurological indicators related to recognition. Both of them may

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