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Electrophysiological correlates of saving-enhanced memory: Exploring similarities to list-method directed forgetting

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Abstract

People regularly outsource parts of their memory onto external memory stores like computers or smartphones. Such cognitive offloading can enhance subsequent memory performance, as referred to the saving-enhanced memory effect (Storm & Stone, 2015). The cognitive mechanisms of this effect are not clear to date, however similarities to list-method directed forgetting (LMDF) have been stated. Here, we examined in 52 participants the electrophysiological (EEG) correlates of the saving-enhanced memory effect and compared our results to earlier LMDF findings (Hanslmayr et al., 2012). For this purpose, EEG alpha power and alpha phase synchrony during the encoding of two word lists were compared as a function of saving or no-saving. We hypothesised that if saving-enhanced memory was related to LMDF, saving in comparison to no-saving between lists should reduce alpha power and alpha phase synchrony during List 2 encoding, two effects that have been related to List 2 encoding benefits and List 1 inhibition in the earlier LMDF work. The results showed no statistically significant saving-enhanced memory effect and no significant effects in EEG alpha power or alpha phase synchrony. Possible explanations for and implications of these non-significant findings are discussed.

KEYWORDS

alpha phase synchrony, alpha power, brain oscillations, cognitive offloading, episodic memory

1 | INTRODUCTION

Nowadays we regularly rely on digital devices to function as external memory stores (e.g., Sparrow et al., 2011). We outsource parts of our memory in order to reduce cognitive demands, hereby performing cognitive offloading (for a review, see Risko & Gilbert, 2016). Indeed, cognitive offloading helps us to reduce the number of facts and knowledge that we would have to remember on our own, freeing cognitive resources for the processing of other information and other cognitively demanding tasks in general (Runge et al., 2019; Storm & Stone, 2015). For instance, saving previously encoded information onto a computer can improve memory for

Abbreviations: CSD, current source density; EEG, electroencephalography; EOG, electrooculogram; FWHM, full power width at half maximum; LMDF, list-method directed forgetting; N, no-save trials; PLV, phase-locking value; S, save trials.

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subsequently encoded other information, which has been referred to as saving-enhanced memory (Storm & Stone, 2015). In the experiments reported by Storm and Stone (2015), participants studied two word lists for later recall testing (repeatedly in six to eight trials using different item material). After study of List 1, participants either saved the list onto a computer and were told that they could reopen and relearn this list before recall testing (save trials) or exited the list without saving (no-save trials). After study of List 2, participants had to recall List 2 items first and List 1 items second in two separate free recall tests (with restudy of List 1 items between recall tests in save trials). The results showed that participants recalled more List 2 items in save trials than in no-save trials, which reflects the saving-enhanced memory effect. In the present study, we investigated the electrophysiological (EEG) correlates of this newly introduced saving-enhanced memory effect.

1.1 | Saving enhanced memory—A variant of directed forgetting?

The precise mechanisms of the saving-enhanced memory effect are not clear to date. One possibility that has been suggested by Storm and Stone (2015) is that saving could function like an implicit forget cue, triggering List 1 as temporarily irrelevant because a file of this list can be reopened and thus restudied at some later time point before recall testing. Indeed, research employing the list-method directed forgetting (LMDF) task demonstrated that cuing participants to intentionally forget previously studied information can enhance memory for subsequently studied other information. In the LMDF task, participants study two item lists. After study of List 1, they are either cued to forget this list (forget condition) or continue remembering this list (remember condition). After study of List 2, participants are tested in separate recall tests on List 1 and List 2 independent of original cuing. The typical finding is that the forget cue impairs recall of List 1 and improves recall of List 2, referred to as List 1 forgetting and List 2 enhancement (for a review, see Pastötter et al., 2017; Sahakyan et al., 2013). Different accounts have been suggested to explain LMDF, including one-mechanism (e.g., Geiselman et al., 1983; Sahakyan & Kelley, 2002) and two-mechanism accounts (e.g., Pastötter & Bäuml, 2010; Sahakyan & Delaney, 2003).

Due to a number of dissociations that have been observed between LMDF effects (e.g., List 2 enhancement typically occurs without List 1 forgetting in item recognition tests; Benjamin, 2006; Pastötter et al., 2016), two-mechanism accounts are commonly preferred as theoretical explanations of LMDF. For instance, Sahakyan and Delaney (2003) proposed a two-mechanism account that attributes List 1 forgetting to a change in internal context (as response to the forget cue when participants think of something other than the item material), inducing context-dependent forgetting, and List 2 enhancement to a change in encoding strategy, with more elaborate encoding of List 2 items after a forget cue than after a remember cue. In contrast, Pastötter and Bäuml (2010) attributed List 1 forgetting to retrieval inhibition, which reduces accessibility of List 1 context during List 2 encoding and final test, and List 2 enhancement to a reset of encoding processes. According to the reset-of-encoding hypothesis, the forget cue abolishes memory load and inattentional encoding that would build up when both lists were to be remembered. This makes the encoding of List 2 items as effective as the encoding of List 1 items (see Pastötter et al., 2012, for an updated two-mechanism account that assumes an additional role of inhibition-induced interference reduction for List 2 enhancement). Runge et al. (2019) showed that short-term effects like a reset of encoding might also play a role in saving-enhanced memory. Besides presenting a replication of saving-enhanced memory, the study showed a related benefit effect for modular arithmetic tasks. Saving recently encoded verbal material benefitted performance in unrelated modular arithmetic tasks that have often been considered an index for working-memory capacity (e.g., Beilock & Carr, 2005; Bellinger et al., 2015; Mattarella-Micke et al., 2011). Hence, a save cue seems to abolish memory load similar to a forget cue, providing more attentional/cognitive resources for subsequent cognitively demanding tasks, not least for the encoding of subsequently presented verbal item material.

Neurocognitive evidence for the two-mechanism account of Pastötter and Bäuml (2010) arose from an LMDF study by Hanslmayr et al. (2012) that examined EEG alpha oscillations (around 10 Hz) during the encoding of the two item lists (see also Bäuml et al., 2008, for an LMDF study that focused on EEG activity during List 2 encoding). This study demonstrated that alpha amplitude (9–11 Hz) during item encoding increased from List 1 to List 2 in the remember condition, but not in the forget condition. Because increases of alpha amplitude during item encoding have been attributed to increases in memory load and inattention (Pastötter et al., 2008, 2011; Sederberg et al., 2006), this finding suggests that the forget cue resets neural activity during List 2 encoding back to List 1 level and thus improves the encoding of List 2 items, which fits with the reset-of-encoding hypothesis by Pastötter and Bäuml (2010). In addition, Hanslmayr et al. (2012) showed that long-range phase synchrony in the upper alpha/lower beta frequency range (11–18 Hz), measured

by means of the phase-locking value (PLV, Lachaux et al., 1999), decreased from List 1 encoding to List 2 encoding in the forget condition, but not in the remember condition. Following the view that memories are represented in widely distributed cortical networks (Fuster, 1997), the decrease in phase synchrony in the forget condition may reflect the inhibition of List 1 context (Pastötter & Bäuml, 2010; for a neurocognitive review on inhibitory forgetting, see Anderson & Hanslmayr, 2014).

1.2 | The present study

The goal of the present study was to investigate the EEG correlates of the saving-enhanced memory effect. Specifically, following the proposal by Storm and Stone (2015) and the findings of Runge et al. (2019), we wanted to test the hypothesis that saving between two item lists is a variant of LMDF. As in LMDF, multiple mechanisms might account for benefits of saving, possibly affecting both the encoding and the recall of List-2 items. In LMDF, two of

TABLE 1 Overview of the hypotheses, the proposed way of analysing them, the respective sampling plan and prospective interpretation

	Hypothesis	Analysis	Sampling plan	Interpretation
1	H0: No difference in List 2 recall between conditions (save vs. no-save trials) H1 (*expected*): Higher recall for List 2 items in save trials compared to no-save trials	One-sided paired *t* test with correct List 2 recall as DV and condition (save vs. no-save) as IV	Calculation of required sample size: $n = 50$ (running $n = 52$ for reasons of balancing) Input parameters: $dz = 0.36$ (as reported by Runge et al., 2019), $\alpha = 0.05$, and $1 - \beta = 0.80$	No significant NHST: Failed replication of the behavioural saving-enhanced memory effect Significant NHST: Replication of the behavioural saving-enhanced memory effect
2	H0: No significant interaction between the factors of condition (save, no-save) and list (List 1, List 2) for alpha power change H1 (*expected*): Significant interaction between the factors of condition (save, no-save) and list (List 1, List 2) for alpha power change → Increase of alpha power change during item encoding from List 1 to List 2 in no-save trials but not in save trials	Non-spatial cluster analyses of the interaction effect based on non-parametric permutation testing (Maris & Oostenveld, 2007) → planned comparisons (*t* tests) averaged over significant electrodes	Performing power calculations for statistical analyses that involve high-dimensional data like the present time-frequency EEG data is challenging. $n = 52$ would be more than twice the sample size analysed in the study by Hanslmayr et al. (2012; $n = 22$), suggesting large enough power for this analysis	No significant alpha cluster: No direct evidence for an encoding reset as it has been observed in LMDF Significant alpha cluster, planned comparisons as expected: Evidence for an encoding reset
3	H0: No significant interaction between the factors of condition (save, no-save) and list (List 1, List 2) for upper alpha/lower beta PLVs H1 (*expected*): significant interaction between the factors of condition (save, no-save) and list (List 1, List 2) for upper alpha/lower beta PLVs → Decrease of upper alpha/lower beta PLVs during item encoding from List 1 to List 2 encoding in save trials but not in no-save trials	Non-spatial cluster analyses of the interaction effect based on non-parametric permutation testing (Maris & Oostenveld, 2007) → planned comparisons (*t* tests) averaged over significant electrodes	Performing power calculations for statistical analyses that involve high-dimensional data like the present time-frequency EEG data is challenging. $n = 52$ would be more than twice the sample size analysed in the study by Hanslmayr et al. (2012; $n = 22$), suggesting large enough power for this analysis	No significant upper alpha/lower beta cluster: No direct evidence for List 1 inhibition as it has been observed in LMDF Significant upper alpha/lower beta cluster, planned comparisons as expected: Evidence for List 1 inhibition

those mechanisms (reset of encoding for List 2 and suppression of List 1) have been linked to separate EEG correlates during List 2 encoding (Hanslmayr et al., 2012). The findings by Runge et al. (2019) suggest that better encoding due to a reset of encoding might also account for the saving-enhanced memory effect. Accordingly, we would expect that alpha amplitude during item encoding increases from List 1 to List 2 in the no-save condition, but not in the save condition, reflecting a reset of encoding (Hanslmayr et al., 2012). Furthermore, if a save cue is indeed a variant of a forget cue that does not only abolish short-term memory load but also impairs accessibility of offloaded List 1 items in long-term memory, we would expect to find possible correlates of such suppression in the EEG. Hence, we wanted to examine whether long-range phase synchrony in the upper alpha/lower beta frequency range decreases from List 1 encoding to List 2 encoding in save trials, but not in no-save trials, possibly reflecting the inhibition of List 1 (Hanslmayr et al., 2012; for an overview of our hypotheses, proposed sampling plans, analysis and prospective interpretations see Table 1). Overall, such findings would clarify how close the saving-enhanced memory effect is related (at the level of brain oscillations) to LMDF. It should be noted that while the present study aimed at addressing the question of whether saving-enhanced memory involves similar mechanisms as LMDF, it did not aim at directly comparing saving-enhanced memory and LMDF in a single experiment.

2 | METHOD[1]

2.1 | Participants

Following the behavioural study by Runge et al. (2019), who reported an effect size $dz = 0.360$ for the saving-enhanced memory effect, and with the additional input parameters $\alpha = 0.05$ and $1 - \beta = 0.80$ for a one-sided paired t test, we calculated a sample size of 50 participants using G*Power 3.1.9.2 (Faul et al., 2007). Yet for reasons of balancing, we needed a multiple of four. Therefore, the experiment was run with a total sample size of 52 participants. This is more than twice the sample size that went into the EEG analysis in the LMDF study by Hanslmayr et al. (2012; $n = 22$).

Participants were undergraduate students at the University of Trier who participated in the study for course credit or payment (20 Euro). Participants' mean age was 24.81 years (SD = 5.16 years; Min = 19 years; Max = 49 years). Forty-three participants were female and nine participants were male. All participants had normal or corrected-to-normal vision; they reported no history of neurological disease. All participants gave written informed consent before examination. The study was conducted in accordance with the Declaration of Helsinki; it was approved by the local ethical review committee at the University of Trier (reference number: 50/2017).

2.2 | Exclusion criteria

Participants who did not follow task instructions (e.g., in the distractor task) should be excluded and replaced by new participants with the same balancing of item material and experimental trials. Regarding EEG analysis, participants with more than five interpolated channels (out of 65 electrodes) should be excluded and replaced by new participants. In addition, participants with less than 15 (out of 30) artefact-free EEG segments per condition and list were to be excluded and replaced (see Hanslmayr et al., 2009, for a simulation experiment showing that EEG oscillatory [de]synchronisation patterns stabilise with 15 segments per condition). No participants should be excluded based on (individual differences in) behavioural results. As it turned out, no participant met these exclusion criteria and thus had to be excluded.

2.3 | Design

Saving was manipulated within participants (save vs. no-save trials). Four save and four no-save trials were conducted for each participant.

2.4 | Materials

The experiment was designed and conducted with E-prime software (Version 2.0, Psychology Software Tools, Sharpsburg, PA). Across eight trials (four save trials, four no-save trials), participants learned and recalled 16 single word lists of 10 common nouns each (four to eight letters long). During breaks between trials, participants solved Sudokus, which were printed and solved by participants with a pen.

2.5 | Procedure

The overall procedure was very similar to the procedure used by Storm and Stone (2015) in Experiment 1

[1]Following in-principle acceptance on 30 Jan 2020, the approved Stage 1 version of this manuscript was preregistered at PsychArchives (https://doi.org/10.23668/psycharchives.2766). This preregistration was performed prior to data collection and analysis.

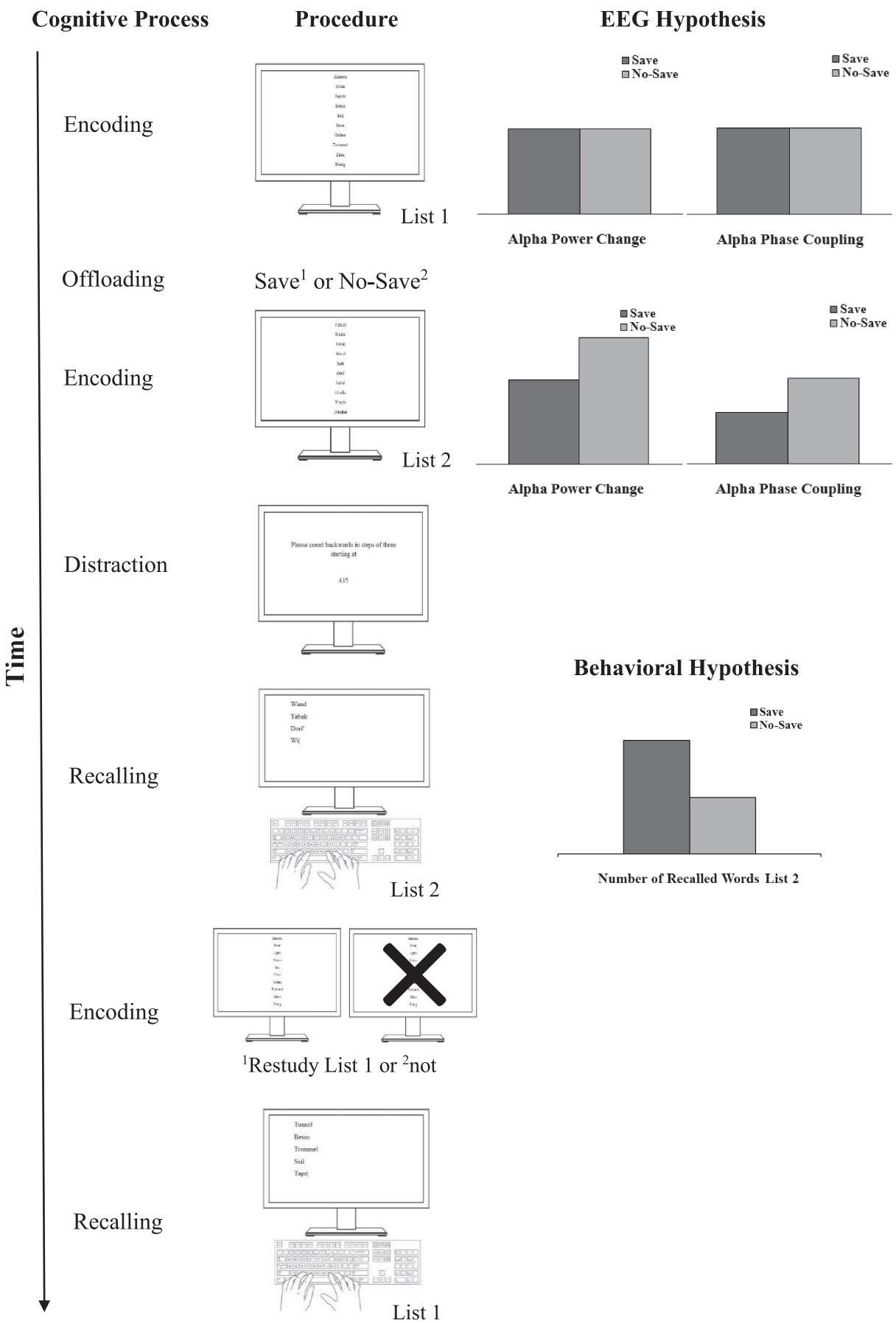
Cognitive Process
Procedure
EEG Hypothesis
Time
Encoding
List 1
Save
No-Save
Alpha Power Change
Alpha Phase Coupling
Offloading
Save[1] or No-Save[2]
Encoding
List 2
Distraction
Please count backwards in steps of three starting at
435
Recalling
Wand
Tabak
Dorf
Wij
List 2
Behavioral Hypothesis
Number of Recalled Words List 2
Encoding
[1]Restudy List 1 or [2]not
Recalling
Tunnel
Beton
Trommel
Seil
Tapet
List 1

FIGURE 1 Sample trial sequence with hypothesized electrophysiological (EEG) and behavioral results. After study of List 1, participants were instructed either to save this file or not to save it. When requested to save the file participants recognized at this point that they could relearn List 1 later on. Next, participants studied List 2 and afterwards solved a distractor task (counting backwards). The test for List 2 followed. In save trials, participants relearned List 1 before being tested for this list. In no-save trials, the test for List 1 directly followed the test for List 2. From List 1 encoding to List 2 encoding we expected to find an increase in alpha power in no-save trails (not in save trials) and a decrease in alpha phase coupling in save trials (not in no-save trials). Besides, we expected to replicate the saving-enhancement effect that is better recall of List 2 items in save trials than in no-save trials

(see Figure 1) with slight changes in the presentation of word lists in order to allow trial based analysis of EEG oscillatory activities in stimulus-induced power changes and long-range phase synchrony. Each word list was equally often presented in save or no-save trials, and as the first list (List 1) or second list (List 2) of a trial, all balanced between participants. Identical to Runge et al. (2019), this balancing was achieved by running four different versions of the experiment. Equal numbers of participants were assigned to each version. Every participant ran through four save (S) and four no-save (N) trials. Depending on the experimental version, participants were assigned to one of two fixed sequences of trials (SNNSSNNS, NSSNNSSN). This assured that, across participants, at each moment during the experiment equally often save and no-save trails appeared. Yet, the participants were told that the sequence of trials was random. To ensure that the participants could easier distinguish the 16 word lists from another, in the experiment lists were numbered consecutively starting with list 1A for the first list of the first trial and list 1B for the second list of the first trial continuing up to lists 8A and 8B for the last trial (note, throughout this manuscript we keep calling all first lists of each trial List 1 and all second lists of each trial List 2). Besides some basic verbal instructions at the beginning of the experiment concerning requested behaviour (e.g., to move as little as possible in order to reduce artefacts in the EEG) all later instructions were presented via screen within the automatized experimental procedure.

The crucial aspect of the experimental procedure was the cue following List 1 encoding (save vs. no-save trials). The 10 nouns of this list were presented one below the other on a single screen, with the list of nouns starting in the upper half of the screen, until all 10 nouns were visible at once (viewing distance: 65 cm; font: Times New Roman; font size: 32; vertical gap between words: 1.9 cm/∼0.75 in.; size of words (corrected for angle of vision): 0.8 cm (0.71 cm)/ ∼0.31 in. (0.28 in.)). The presentation of each word was preceded by a 2-s fixation cross that was shown centrally to the position of the next word. 2 s after onset of each word, the next fixation cross was shown (words 1 to 9) or the list ended (word 10) after 40 s. Participants were instructed to always keep their focus on presented fixation crosses and the most recent word to appear. In order to ensure that participants followed this instruction we told participants that an eye tracker would capture their eye movements throughout the experiment. Note that although we did place an eye tracker below the screen, this eye tracker did not collect any data. After List 1 encoding, two different instructions could appear, depending on the type of trial. In save trials, participants were instructed that List 1 would be saved and therefore accessible again for a second encoding phase. After this instruction, participants had to press the key "s" in order to allegedly save List 1, triggering a message box that says that List 1 has now been saved. In contrast, in no-save trials, participants were told that List 1 would not be saved, which omits the possibility to relearn this list later on. In these trials, participants had to press the key "n," triggering a message box saying that List 1 has not been saved.

The procedural steps after the instruction of saving or not saving List 1 were again identical across both types of trials. First, participants studied List 2 in the same way as they had studied List 1. Again, the 10 nouns of the list appeared on the screen one below the other. Afterwards, participants did a distractor task (counting backward in steps of three from a three-digit number for 30 s). Then, participants had to recall List 2 in a free recall test, lasting 30 s, by typing all remembered words onto a blank screen so that their answers were registered. In no-save trials, this recall test was directly followed by the recall test for List 1 (30 s). In save trials, participants got the possibility to relearn List 1 (with same item presentation order) before being tested on it. To get familiar with this procedure and the consequences of saving or not saving List 1, participants ran through one save and one no-save trial for practice. Afterwards participants proceeded through six experimental trials, i.e., three save trials and three no-save trials. Between trials, participants had to fulfil an unrelated distractor task (solving a Sudoku for 1 min). Similar procedures with similar verbal material (same word length, similar amount of words per word list) have been used in previous studies (e.g., Runge et al., 2019; Storm & Stone, 2015). In these studies between 30% and 60% of the verbal material was recalled (despite changes in the amount of words per word lists). Therefore, no

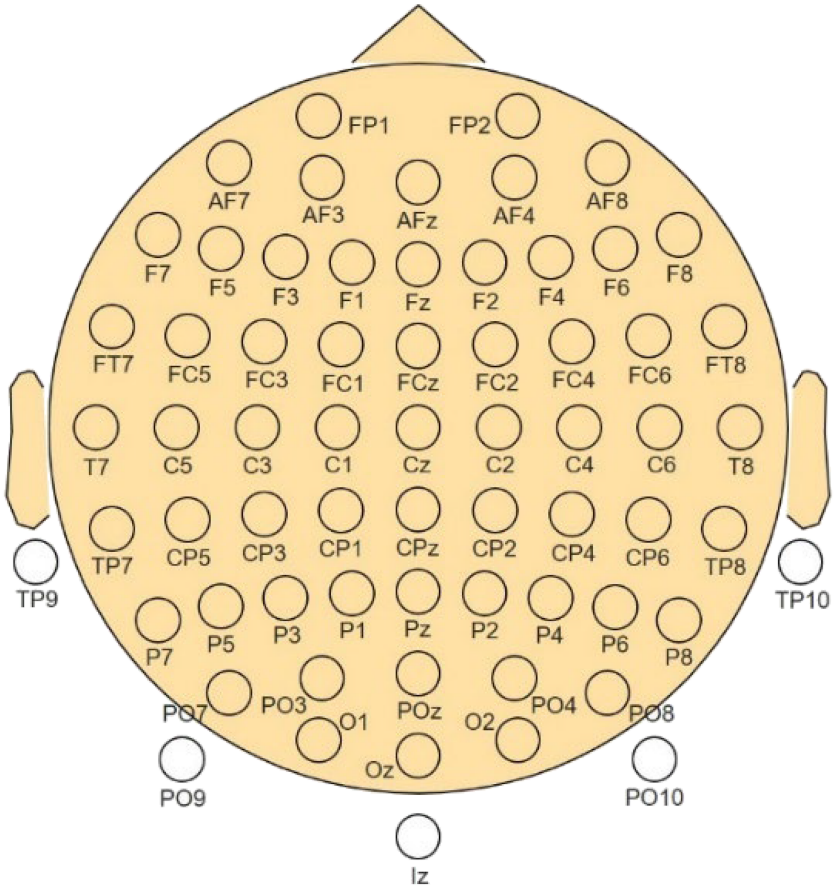

FIGURE 2 Montage of the 65 scalp electrodes. FCz served as original reference (additional ground electrode at FPz; four additional electrooculogram (EOG) electrodes were used, but see Footnote 2)

bottom or ceiling effects regarding the use of the present verbal material were expected.

2.6 | Recording of EEG data

During the encoding phase of Lists 1 and 2, scalp EEG was recorded from 65 Ag/AgCl electrodes arranged according to the 10–10 electrode system with reference to FCz (EC80, Montage No. 1, Easycap, Herrsching, Germany) in a shielded booth (see Figure 2). Ground electrode was placed at location AFz.

The electrooculogram (EOG) was recorded from four bipolar channels, positioned on the inferior and superior regions of the left eye and the outer canthi of both eyes, in order to monitor the vertical and horizontal EOG.[2] Electrode-skin impedance was kept below 5 kΩ for all scalp and EOG electrodes. Signals were digitalized with a sampling rate of 500 Hz and amplified between 0.016 and 250 Hz (BrainAmp, BrainVision Recorder, v1.20, Brain Products, Gilching, Germany).

2.7 | Preprocessing of EEG data

EEG recordings were re-referenced offline against average reference and EOG corrected by using calibration data and generating individual EOG artefact coefficients, as implemented in BESA Research (v7.0, BESA Software, Gräfelfing, Germany). After EOG-correction, remaining artefacts were marked by careful visual inspection. EEG signals of single electrodes showing heavy artefacts throughout the whole session were interpolated using a spline interpolation in BESA research (mean number of channels per subject = 1.77; SD = 1.72; max = 5). Artefact-free EEG data were segmented into epochs ranging from −3.0 to 3.0 s around the onset of words. To avoid filter artefacts at the edges of segments, time-frequency analyses were restricted to intervals ranging from −2.0 to 2.0 s around word onset, which covers all time points of each list. For each subject, a maximum number of 30 segments per list and condition went into analysis of time-frequency data.

[2]Note that due to the Corona pandemic and enhanced hygiene and safety measures, no face electrodes were applied in 30 out of the 52 participants. For those 30 participants, one bipolar montage was used at electrode positions AF9 and AF10 for the monitoring of horizontal eye movements, whereas vertical eye movements and blinks were derived from frontal scalp electrodes. Note that this is a minor deviation in the research plan at Stage 2 of the registered report.

2.8 | Time-frequency decomposition

The EEG data were transformed into the time-frequency domain using a complex demodulation algorithm, which is implemented in BESA Research 7.0 (see Hoechstetter et al., 2004). The algorithm consists of a multiplication of the time domain signal with a complex periodic exponential function, having a frequency equal to the frequency under analysis, and subsequent low-pass filtering. The low-pass filter is a finite impulse response filter of Gaussian shape in the time domain, which is related to the envelope of the moving window in wavelet analysis. The data were filtered in the frequency range from 2 to 20 Hz. Time resolution was set to 78.8 ms (full power width at half maximum; FWHM), and frequency resolution to 1.42 Hz (FWHM). Time-frequency data were exported in bins of 50 ms and 1 Hz.

2.9 | Analysis of power changes

Stimulus-induced power changes were determined by calculating temporal-spectral evolution, that is, power changes during word presentation for all time-frequency points with power increases or decreases at time point t and frequency f related to mean power at frequency f over the prestimulus baseline interval (Pfurtscheller & Aranibar, 1977; Pfurtscheller & Lopes da Silva, 1999). Following Hanslmayr et al. (2012), the baseline interval was set from −0.5 s to stimulus onset. Permutation-based cluster analysis (Maris & Oostenveld, 2007) was calculated to examine the interaction between conditions (save, no-save) and lists (List 1, List 2), as implemented in BESA Statistics (v2.1, BESA Software).[3]

In the first step, non-spatial cluster analysis was calculated, in which time-frequency spectrograms of power changes were averaged across the 65 electrodes and differences in averaged power changes between List 1 and List 2 were contrasted between conditions in single t tests on difference scores in order to test the interaction between the factors of condition (save, no-save) and list (List 1, List 2) for power changes (as referred to in Table 1). Specifically, two-tailed t tests for all time-frequency points (41 [time bins during stimulus presentation] * 19 [frequency bins from 2 to 20 Hz]) were calculated and clusters of contiguous significant data points ($p < 0.05$) were derived. For each empirical cluster, the sum of t values of the single significant data points was kept as a test statistic. Random permutation tests (10,000 runs) were run in which the sum test statistic was repeatedly calculated for randomly shuffled data sets, with the data randomly reordered across save and no-save conditions and the permutation-based cluster with the highest sum of t values was kept. Test statistics for empirical clusters were compared to the null distribution of the permutation-based clusters and a p value for the empirically derived cluster(s) was calculated.

In the second step, significant empirical clusters with a p value below 0.05 would have gone into analysis of spatial topography. For each cluster, power changes would be averaged across data points of the cluster's maximum time range and maximum frequency range, separately for each electrode. Differences in averaged power changes between List 1 and List 2 would be contrasted between conditions (save, no-save). Two-tailed t tests would be calculated for all electrodes. Spatial topographies would be identified and plotted by considering those electrodes that were significant in the t test. No additional cluster analysis would be calculated. Thus, both clustered and scattered spatial effects would be considered in spatial analysis.

Finally, power changes in a significant cluster's time-frequency range would be averaged across significant electrodes and differences between lists (List 1, List 2) would be analysed in planned comparisons separately for the two conditions (save, no-save) with SPSS (Version 24.0), expecting a significant increase of (alpha) power change from List 1 to List 2 in the no-save condition, but no significant difference in (alpha) power change between lists in the save condition. Time courses of significant effects would be plotted, respectively.

2.10 | Analysis of phase synchrony

Before phase synchrony calculation, a current source density (CSD) transformation was applied to the EEG data using BESA Research. The phase synchrony values were calculated following the procedure of Lachaux et al. (1999), as implemented in BESA Connectivity (v1.0).[4] As described in the study by Hanslmayr et al. (2012), this procedure delivers a value that ranges from 0 to 1, indicating minimal to maximal phase synchrony, respectively. Phase locking values (PLVs) were calculated for all possible pairs of electrodes, all time bins from −2.0 to 2.0 s around word onset, and

[3]BESA Statistics (v2.1) was used instead of BESA Statistics (v2.0), which is a minor deviation in the research plan at Stage 2 of the registered report.

[4]BESA Connectivity (v1.0) was used instead of BESA Research (v7.0), which is a minor deviation in the research plan at Stage 2 of the registered report.

all frequency bins from 2 to 20 Hz, separately for conditions (save, no-save) and lists (List 1, List 2).

In the first step, non-spatial cluster analysis were calculated. PLVs were averaged across the 41 time bins and 65 electrodes and differences in averaged PLVs between List 1 and List 2 were contrasted between conditions in single *t* tests on difference scores in order to test the interaction between the factors of condition (save, no-save) and list (List 1, List 2) for PLVs (as referred to in Table 1). Two-tailed *t* tests for all frequency points (19 [frequency bins from 2 to 20 Hz]) were calculated and clusters of contiguous significant frequency points ($p < 0.05$) were derived. For each empirical cluster, the sum of *t* values of the single significant frequency points was kept as a test statistic. Random permutation tests (10,000 runs) were run in which the sum test statistic was repeatedly calculated for randomly shuffled data sets, with the data randomly reordered across save and no-save conditions and the permutation-based cluster with the highest sum of *t* values was kept. Test statistics for empirical clusters were compared to the null distribution of the permutation-based clusters and a *p* value for the empirically derived cluster(s) was calculated.

In the second step, significant empirical clusters with a *p* value below 0.05 would have gone into analysis of spatial topography. For each cluster, PLVs would be averaged across data points of the cluster's maximum time range and maximum frequency range, separately for each electrode pair. Differences in PLVs between List 1 and List 2 would be contrasted between conditions (save, no-save). Two-tailed t tests would be calculated for all electrode pairs. Spatial topographies would be identified and plotted by considering those electrodes that were significant in the *t* test. No additional cluster analysis would be calculated. The plotting of spatial topographies would be used to graphically describe the distribution of PLV effects over the scalp; no additional inferential statistics regarding the spatial distribution effects would be calculated.

Finally, PLVs in a significant cluster's frequency range would be averaged across significant electrodes and differences between lists (List 1, List 2) would be analysed in planned comparisons separately for the two conditions (save, no-save) with SPSS (Version 24.0), expecting a significant decrease of (upper alpha/lower beta) PLVs from List 1 to List 2 in the save condition, but no significant difference in (upper alpha/lower beta) PLVs in the no-save condition. Time courses of significant effects would be plotted, respectively.

Because trial numbers can bias phase synchronisation measures, following Hanslmayr et al. (2012), it was statistically checked whether there were significant differences between trial numbers across conditions and lists. Mean numbers of artefact-free trials were 28.00 (SD = 2.17, min = 20) for List 1 and 28.52 (SD = 1.78, min = 21) for List 2 in the save condition, and 28.10 (SD = 2.28, min = 19) for List 1 and 28.40 (SD = 1.90, min = 23) for List 2 in the no-save condition. Repeated-measures analysis of variance (ANOVA) with the two factors of list (List 1, List 2) and condition (save, no-save) showed no significant main effect of list, $F(1,51) = 3.18$, $MSE = 2.79, p = 0.080, \eta_p^2 = 0.059$, no significant main effect of condition, $F(1,51) < 1$, and no significant interaction between the two factors, $F(1,51) < 1$. Nevertheless, additional control analyses were calculated (for both power change and PLVs), in which the numbers of trials were equated by means of randomly selecting the minimum number of available trials (≥15) per condition and list for each.

Note that in contrast to the behavioural analysis, in which a directional alternative hypothesis was used (see below) based on expectation of a directional saving-enhanced memory effect (e.g., Runge et al., 2019; Storm & Stone, 2015), non-directional alternative hypotheses were used in the EEG analyses in order to leave some room for exploratory analysis (e.g., effects that are opposite direction to the ones expected on the basis of the earlier EEG work in LMDF).

2.11 | Analysis of behavioural data

Behavioural data were analysed using SPSS (Version 24.0). The mean number of words correctly recalled in the List 2 recall test(s) were analysed between experimental conditions (save vs. no-save) by calculating a one-sided paired *t* test. This comparison of two conditions is equivalent to the common approach in LMDF where a forget condition is compared with a remember condition. Hence, the variable of interest is a difference score derived from these comparisons. An actual baseline condition is not common in these fields of research and would not serve much purpose. In addition, a possible influence of trial block (Block 1 vs. Block 2 vs. Block 3) on these difference scores was examined in repeated-measures ANOVA with the two factors of experimental condition and trial block. The variable trial block divides all trials (excluding practice trials) into three blocks. Block 1 includes the first save trial and the first no-save trial, Block 2 the second save trial and the second no-save trial, and Block 3 the third save trial and the third no-save trial. Hence, this analysis examined possible variations of the difference scores mentioned above throughout the experiment. For the mean number of words correctly recalled from List 1, the same analyses

go as for the words correctly recalled from List 2. Finding a behavioural saving-enhanced memory effect is a prerequisite for all EEG based analyses mentioned.[5] Note that the behavioural saving-enhanced memory effect has been replicated several times with the method we used here (e.g., Runge et al., 2019; Storm & Stone, 2015).

3 | RESULTS

3.1 | Behavioural results

Regarding list 2, the one-sided paired t test, which compared mean number of correctly recalled List 2 items, averaged across trial blocks 1 to 3, between the save (4.93 items) and the no-save condition (4.72 items), showed no significant saving enhanced memory effect, $t_{51} = 1.17, p = 0.123, dz = 0.163$. In addition, regarding the number of correctly recalled List 2 items, the ANOVA with the factors of condition (save, no-save) and trial block (Block 1, Block 2, Block 3) showed no significant main effect of condition, $F(1,51) = 1.38$, $MSE = 2.38, p = 0.246, \eta_p^2 = 0.026$, no significant main effect of trial block, $F(1.79, 91.10) < 1$ (Greenhouse–Geisser corrected), and no significant interaction between the two factors, $F(2,102) < 1$. Thus, throughout the experiment, no significant saving enhanced memory effect was observed (see Figure 3a). For the purpose of illustration, Figure 3b shows the dz estimates of the difference scores in List 2 recall between the save and no-save conditions, averaged across trial blocks 1 to 3, and the respective p values from one-sided paired t tests conducted after each pair of observations, that is, after each tested subject.[6]

Regarding the number of correctly recalled List 1 items, the ANOVA with the factors of condition (save, no-save) and trial block (Block 1, Block 2, Block 3) revealed a significant main effect of condition, $F(1,51) = 340.01, MSE = 3.38, p < 0.001, \eta_p^2 = 0.870$, but no significant main effect of trial block, $F(1.74, 88.98) = 1.74, MSE = 3.70, p = 0.186, \eta_p^2 = 0.033$ (Greenhouse–Geisser corrected), and no significant interaction between the two factors, $F(2,102) < 1$. The main effect of condition reflects the benefits of relearning List 1 before testing in the save condition.

[5]For the sake of completeness, the EEG data were analysed although the behavioural saving-enhanced memory effect was not significant. This is a minor deviation in the research plan at Stage 2 of the registered report.

[6]Note that this illustrative simulation was not planned at Stage 1 and thus is a minor deviation in the research plan at Stage 2 of the registered report.

3.2 | EEG power changes

Non-spatial cluster analysis, which tested the interaction between the factors of condition (save, no-save) and list (List 1, List 2) with time-frequency spectrograms of power changes (uncorrected for number of trials) averaged across the 65 electrodes, revealed no significant empirical clusters, all $ps \geq 0.310$ (see Figure 4). Consistently, the additional control analysis, in which the numbers of trials per condition and list were equated for each subject showed no significant clusters, all $ps \geq 0.376$. No further (spatial) analyses were calculated.

3.3 | EEG phase synchrony

Non-spatial cluster analysis, which tested the interaction between the factors of condition (save, no-save) and list (List 1, List 2) with time-frequency spectrograms of PLV data (uncorrected for number of trials) averaged across the 41 time bins and 65 electrodes, revealed no significant frequency points in the single t tests, all $ps > 0.05$ (see Figure 5), and thus no empirical PLV cluster. Consistently, the additional control analysis (corrected for number of trials) showed no significant frequency points in the single t tests, all $ps > 0.05$. No further (spatial) analyses were calculated.

4 | DISCUSSION

The results supported none of the expected hypotheses. The behavioural results showed no statistically significant effect of saving List 1 on recall performance for List 2, that is, no saving-enhanced memory effect (Hypothesis 1; Table 1), which was found to be significant in earlier published work (Runge et al., 2019; Storm & Stone, 2015). In addition, the EEG results showed no statistically significant differences in oscillatory brain activities between the save and no-save conditions. First, alpha amplitude did not increase to a significantly larger degree from List 1 to List 2 encoding in the no-save condition than in the save condition (Hypothesis 2), as it should be expected based on the reset-of-encoding hypothesis taken from LMDF research (Hanslmayr et al., 2012). Second, upper alpha/lower beta PLVs did not decrease to a significantly larger degree from List 1 to List 2 encoding in the save condition than in the no-save condition (Hypothesis 3), as it should be expected if saving induces suppression of List 1 as the forget cue does in LMDF research (Hanslmayr et al., 2012). However, because no significant behavioural saving-enhanced memory effect emerged in

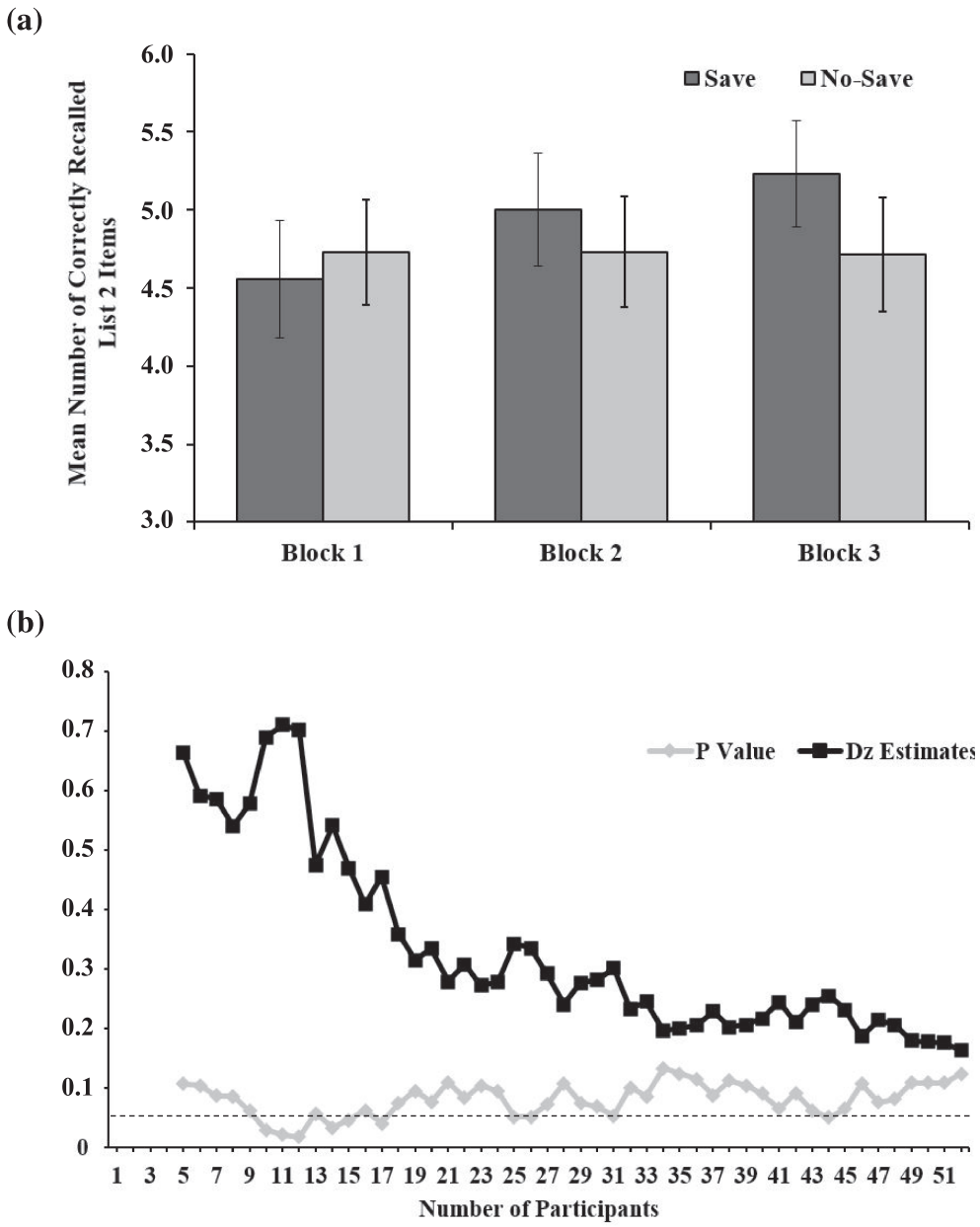

FIGURE 3 Behavioral results. (a) Number of correctly recalled List 2 and List 1 items as a function of condition (save, no-save) and trial block (Block 1 vs. Block 2 vs. Block 3). Error bars show standard errors of the mean. (c) Illustrative plot of dz estimates of the difference scores in List 2 recall between the save and no-save conditions, averaged across trial blocks 1 to 3, and the respective *p* values from one-sided paired *t* tests calculated after each pair of observations (starting from Subject 5)

the present study, the nonfinding of significant EEG effects must be interpreted with caution. In fact, finding a behavioural saving-enhanced memory effect could be considered a prerequisite for valid interpretation of EEG findings. To that end, based on the present results, any conclusion regarding the (dis)similarity of EEG oscillatory correlates of saving-enhanced memory and LMDF effects would be premature.

What are possible reasons why the behavioural saving-enhanced memory effect did not replicate? First, there are methodological differences between the present study and earlier work that may have contributed to the differences in results. The present procedure tried to combine the standard procedures that were used in earlier saving-enhanced memory and LMDF research. In previous behavioural research on the saving-enhanced memory effect, the items of a list were presented simultaneously on a single display (Runge et al., 2019; Storm & Stone, 2015), whereas in EEG research on LMDF, the items were presented sequentially on different displays (e.g., Bäuml et al., 2008; Hanslmayr et al., 2012). Note that the sequential presentation of items is necessary for event-related analysis of the EEG data. In the present study, the two procedures were combined and the list items were presented sequentially one below the other on a single display. This led to relatively longer list presentation times (40 s for each list consisting of 10 items) compared to the previous saving-enhanced memory research (15 s for each list consisting of eight items; Runge et al., 2019). While it is important to emphasise

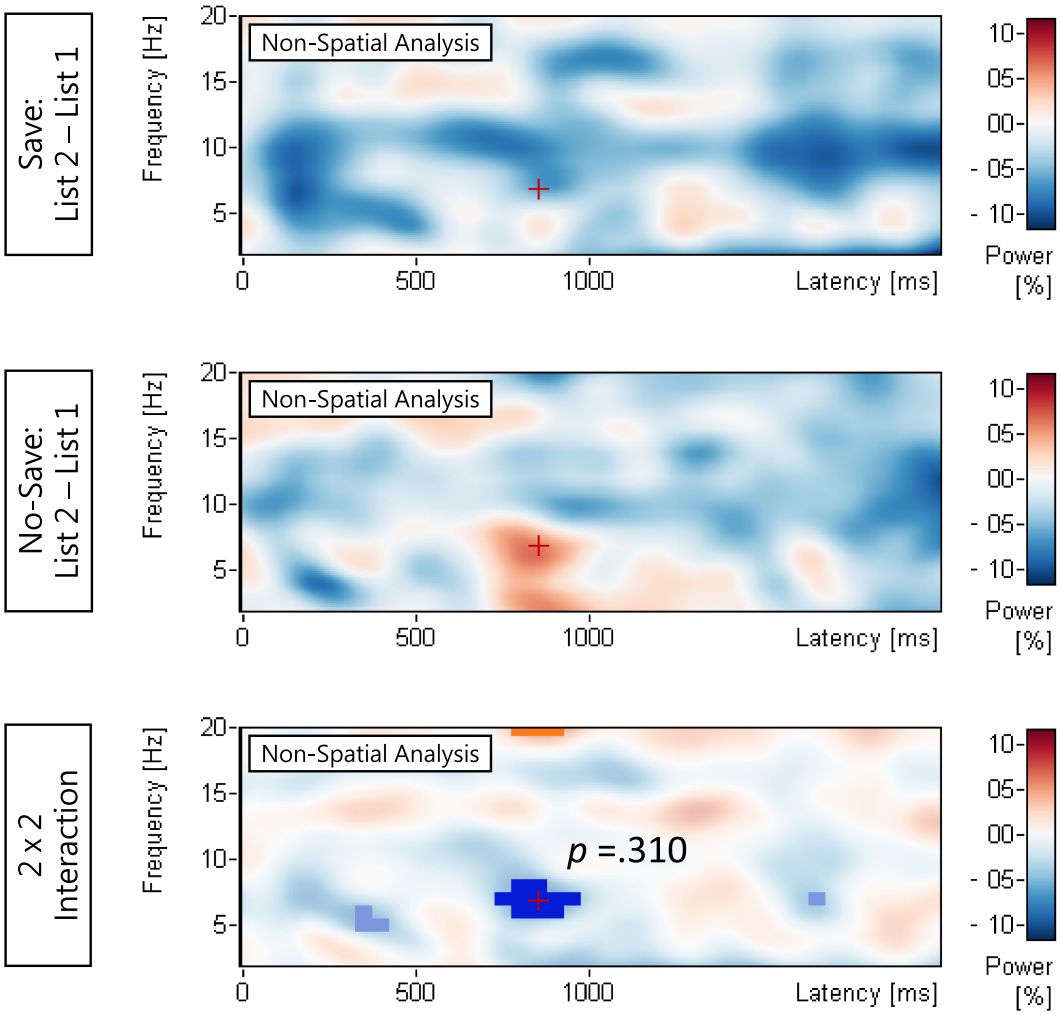

FIGURE 4 Electrophysiological (EEG) power results of the non-spatial cluster analysis. Upper panels: Time-frequency spectrograms of power changes from List 1 to List 2 in the save condition and the no-save condition. Lower panel: Time-frequency spectrogram of the interaction between condition (save, no-save) and List (List 1, List 2). The largest empirical cluster was not significant in the permutation test

that the relatively longer presentation time did not create an obvious ceiling effect in List 2 recall rate in the present study, arguably, the relatively longer presentation time and also the sequential presentation of items may have affected participants' encoding strategy during list learning, which could have affected the saving-enhanced memory effect. This issue needs to be addressed in future research.

Furthermore, it cannot be ruled out that biases in publishing behaviour and questionable research practices (see Simmons et al., 2011) have contributed to the different outcomes between the present and earlier research. One such bias is the publication bias, which can increase the number of reported false positive findings and lead to overestimation of true effect sizes (see Bakker et al., 2012). Registered reports safeguard against publication bias and questionable research practices in psychological science (Scheel et al., in press). Indeed, registered reports publish a much smaller proportion of positive results (44% vs. 96%; Scheel et al., in press) and clearly smaller estimated effect sizes in comparison to standard (not preregistered) reports ($r = 0.16$ vs. $r = 0.36$; Schäfer & Schwarz, 2019). Thus, it could be argued that the saving-enhanced memory effect (like many other effects in the psychological literature including LMDF effects) has been overestimated in the past standard reports and may be smaller than assumed. Accordingly, a smaller population effect would require a larger sample size to produce statistically significant results.

To conclude, the nonfinding of a significant saving-enhanced memory effect in participants' behaviour makes conclusions regarding the neural correlates of the effect and possible (dis)similarities to LMDF research

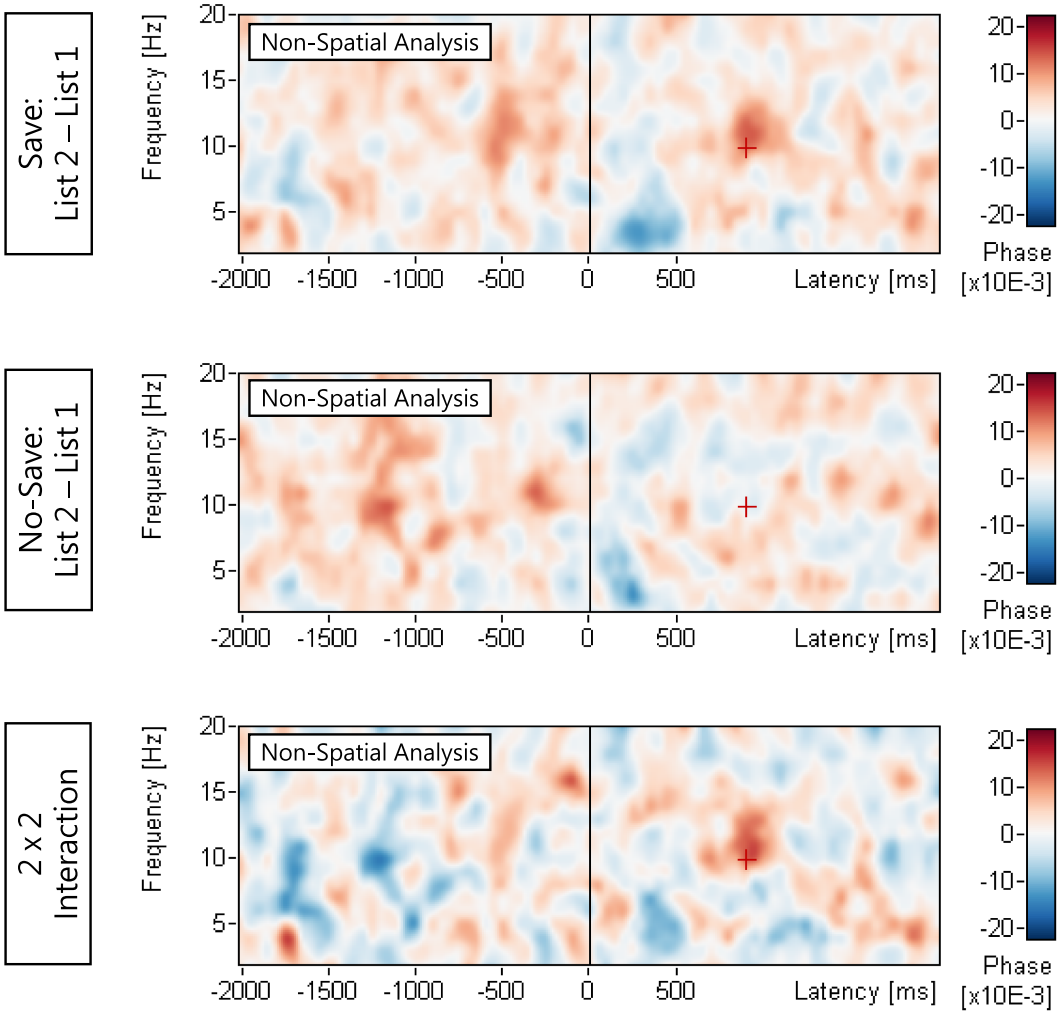

FIGURE 5 Electrophysiological (EEG) phase-locking value (PLV) results of the non-spatial cluster analysis. Upper panels: Time-frequency spectrograms of PLV changes from List 1 to List 2 in the save condition and the no-save condition. Lower panel: Time-frequency spectrogram of the interaction between condition (save, no-save) and List (List 1, List 2). Cluster analysis was based on PLV data averaged over time. No frequency point showed a significant interaction effect, all *ps* > .05, in the single (uncorrected) *t* tests on the difference scores

difficult if not impossible. Hence, the answer to the question whether saving between two lists is a variant of LMDF and is characterised by the same or different EEG oscillatory correlates (and cognitive mechanisms) as reported in LMDF research has to be postponed. Future experiments are necessary that re-examine the EEG oscillatory correlates of the saving-enhanced memory effect—and ideally also of LMDF—with larger statistical power and sample size.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTION

All four authors designed the experiment. YR analysed the behavioural data. BP analysed the EEG data. YR and BP drafted the stage 2 manuscript. TT and CF provided critical revisions. All authors approved the final version of the stage 2 manuscript for submission.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The raw data, codebook including digital study materials, analysis codes and batches, and laboratory log for all

published results have been uploaded to OSF (https://osf.io/6w879/; https://doi.org/10.17605/OSF.IO/6W879).

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