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The Contribution of Encoding and Retrieval Processes to Proactive Interference

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Proactive interference (PI) refers to the finding that memory for recently studied (target) material can be impaired by the prior study of other (nontarget) material. Previous accounts of PI differed in whether they attributed PI to impaired retrieval or impaired encoding. Here, we suggest an integrated encoding-retrieval account, which assigns a role for each of the 2 types of processes in buildup of PI. Employing a typical PI task, we examined (a) the role of encoding processes in PI by recording scalp EEG during study of nontarget and target lists, and (b) the role of retrieval processes in PI by measuring recall totals and response latencies in target list recall. In addition, we measured subjects' working memory capacity (WMC). Behaviorally, the PI effect arose in both recall totals and response latencies, indicating PI at the sampling and the recovery stage of recall. Neurally, we found an increase in electrophysiological activities in the theta frequency band (5–8 Hz) from nontarget to target list encoding, indicating an increase in memory load during target list encoding. The results demonstrate that impaired retrieval and impaired encoding can contribute to PI. They also show that WMC affects PI. For both encoding and retrieval processes, PI was reduced in high-WMC subjects, suggesting that these subjects are able to separate target from nontarget information and create stronger focus on the target material.

Keywords: episodic memory, proactive interference, encoding, retrieval, working memory

Proactive interference (PI) refers to the finding that previously studied information can impair memory for more recently studied information (e.g., Underwood, 1957). In a typical PI experiment, subjects study a target list and are tested on it. In the PI condition, subjects are asked to learn additional nontarget material prior to the study of the target list, whereas in the no-PI condition, they engage in an unrelated task instead. Typically, target list recall is impaired in the PI condition relative to the no-PI condition, which reflects the PI finding. PI has been extensively studied during past decades. The results of this research indicate that PI is a very robust finding and that it may even reflect one of the major causes of forgetting in human memory (for reviews, see Anderson & Neely, 1996; Crowder, 1976).

Accounts of Proactive Interference

Over the years, several accounts have been suggested to explain the PI effect, some of them attributing PI to a problem at the retrieval stage and others to a problem at the encoding stage. The most prominent retrieval account of PI is temporal discrimination theory. This theory suggests that buildup of PI is caused by a failure to distinguish items from the most recent target list from items that appeared on the earlier nontarget lists. The proposal is that, during recall of the (most recent) target list, subjects may not be able to focus their memory search on the target list, but rather include items from the preceding nontarget material into their mental search set, thus impairing target list recall (Baddeley, 1990; Crowder, 1976; Wixted & Rohrer, 1993). An alternative retrieval account of PI is the generation failure hypothesis, which explains PI through a reduced ability to access the target items' memory representation, although the account fails to specify a concrete mechanism that may mediate the suggested generation failure (Dillon & Thomas, 1975). Finally, the PI effect has been attributed to the encoding stage, suggesting that attentional resources may decrease and memory load increase from initial encoding of the nontarget list(s) to the final encoding of the target list. Such impairments may arise from deteriorated buffer operations in a limited rehearsal buffer and/or memory reactivation and competition of previously encoded nontarget items, which may impair target list encoding and thus reduce later recall of the target items (Crowder, 1976; Pastötter, Schicker, Niedernhuber, & Bäuml, 2011).

For each of the three accounts, results have been reported that are consistent with the accounts' main assumptions, although the accounts vary in the extent to which they have been tested to date. There is relatively strong evidence for a role of discrimination processes in PI (Bäuml & Kliegl, 2013; Unsworth, Brewer, & Spillers, 2013; Wixted & Rohrer, 1993). Wixted and Rohrer (1993), for instance, found that the preceding study of nontarget lists increases response latencies for the target items. Because latencies can index the size of the mental search set during retrieval (e.g., McGill, 1963), the finding indicates that memory search becomes less focused in the presence of nontarget material, which is at the core of temporal discrimination theory. There is only moderate evidence for a critical role of generation failure in PI. The evidence is largely based on the finding that, at test, subjects can be able to discriminate between previously studied

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nontarget and more recently studied target material without being able to recall the target items, a finding regarded as indicative of a generation failure (Dillon & Thomas, 1975). The encoding account of PI, finally, has hardly been tested to date and evidence for the contribution of encoding factors is solely based on studies that did not include a no-PI baseline condition. Early support for the account was found in a study showing that pupillary size—which is regarded as an index of attention (Kahnemann & Beatty, 1966)—can decrease across successive study lists, suggesting an increase in inattention with amount of encoded material (Engle, 1975). More recent support arises mainly from studies measuring oscillatory electrophysiological activity during item encoding. The finding is that during encoding of multiple lists, activities in the theta (5–8 Hz) and alpha (10–13 Hz) frequency bands increase from early to later lists (e.g., Pastötter, Bäuml, & Hanslmayr, 2008; Pastötter et al., 2011). Because increases in theta activity in the human EEG have been linked to memory load (Jensen & Tesche, 2002; Onton, Delorme, & Makeig, 2005; Sederberg et al., 2006) and increases in alpha activity to inattention (Klimesch, 2012; Palva & Palva, 2007; Pastötter et al., 2011), these findings suggest that the preceding encoding of (nontarget) material can impair subsequent encoding of (target) material, which may induce PI.

An Integrated Encoding-Retrieval Account of Proactive Interference

By attributing the PI effect to either impaired encoding or impaired retrieval, the PI accounts mentioned above emphasize very different factors that may mediate the PI effect. Importantly, however, these contrasting views are not mutually exclusive and both impaired encoding and impaired retrieval may play a role in PI, as is indicated by the fact that each of the two factors can explain results on PI that are not easily captured by the other factor. For instance, the finding of increased response latencies in the presence of PI (e.g., Wixted & Rohrer, 1993) is highly consistent with the hypothesis of reduced temporal discrimination of target items as caused by the coactivation of nontarget items at test, but is not easily explained by impaired encoding (see also Discussion). The finding of increased electrophysiological activities during target list encoding in the theta and alpha bands of the EEG is highly consistent with the hypothesis of incomplete memory representations of the target items, but cannot be captured by impaired retrieval. In this study, we therefore introduce an integrated account, assuming that both encoding and retrieval processes can contribute to PI. In particular, on the basis of two-stage models of recall, the account assumes that retrieval problems can arise both at the sampling and the recovery stage of memory retrieval.

Several prominent models of memory retrieval have conceptualized recall as a two-stage process (Gronlund & Shiffrin, 1986; Raaijmakers & Shiffrin, 1981; Rohrer, 1996; Wixted & Rohrer, 1994; for alternative single-stage accounts that capture the recall process via a set of accumulators based solely on absolute memory strength, see Polyn, Norman, & Kahana, 2009; Sederberg, Howard, & Kahana, 2008). Two-stage models assume that, in the first stage, items are randomly sampled from a search set that has been delimited by either external or internally generated context cues. The sampling process is assumed to occur according to a relative-strength rule, which says that the probability of sampling an item depends on the size of the mental search set and equals the item's absolute strength divided by the sum of all absolute item strengths within the set (e.g., Shiffrin, 1970). Because response latencies have been shown to measure an item's relative strength in the search set, they provide a window into the sampling stage of recall (e.g., Rohrer, 1996; Wixted & Rohrer, 1993, 1994). In the second stage, sampled items whose absolute strength exceeds some threshold are assumed to be recovered into consciousness. As a consequence, stronger items with a relatively complete memory representation may be recovered, whereas weaker items with less complete memory representation may not, even if they were successfully sampled before. Following this conceptualization, an item's probability of being recalled, like latency, is a measure of its relative strength because it depends on preceding successful sampling. However, in contrast to latency, it is also a measure of its absolute strength and thus provides a window into the recovery stage of recall.

The present integrated encoding-retrieval account of PI follows temporal discrimination theory and assumes first that the preceding encoding of nontarget lists can induce a discrimination problem for target list items at recall (e.g., Wixted & Rohrer, 1993). Specifically, when nontarget lists were studied previously, subjects may employ inappropriate context cues to delimit their mental search set and thus may include also nontarget items into the search set. Such inclusion of nontarget items should reduce the relative strength of the target items and thus create a sampling problem at recall, increasing response latencies for the target items. The account next assumes that the encoding of the target list items can be impaired by the preceding encoding of the nontarget list items. The preceding study of the nontarget lists may increase memory load and inattention for the target list and thus create less complete memory representations of the target items. The increase in memory load and inattention should affect the electrophysiological activity in the theta and alpha bands of the EEG during target list encoding (e.g., Pastötter et al., 2008, 2011) and the impaired encoding induce a recovery problem at recall, preventing the target items from achieving the recovery threshold and thus reducing recall totals. Consistently, the results of previous studies showed that power increases in the theta and alpha bands of the human EEG are related to a decrease in response totals (e.g., Pastötter et al., 2008, 2011; Sederberg et al., 2006; Serruya, Sederberg, & Kahana, 2014). It is the goal of the present study to validate this integrated encoding-retrieval account of PI by employing EEG methods to examine the encoding of target list items, and response latencies and recall totals to examine retrieval of target list items both at the sampling and the recovery stage of recall.[1]

The Possible Role of Working Memory Capacity for Proactive Interference

Individuals typically differ in memory performance. A particularly critical factor for this variation is differences in individuals' working memory capacity (WMC). WMC has been argued to reflect people's ability to retain cognitive representations in an

[1] While both the impaired temporal discrimination hypothesis and the impaired encoding hypothesis specify mechanisms that may induce PI, Dillon and Thomas' (1975) generation failure hypothesis does not propose such mechanism. Due to this, the exact theoretical status of the hypothesis is unclear. For instance, although originally introduced as a retrieval deficit hypothesis, generation failure may also reflect an encoding deficit, with the impaired generation of target items being induced by impaired target list encoding. Due to this lack of specification and for parsimony reasons, we do not include generation failure as another factor into the suggested PI account.

active state in the presence of interfering information (e.g., Kane & Engle, 2002). Consistently, WMC appears to be related to individuals' resistance to PI, as is indicated by studies manipulating interference-relevant variables within the WMC task itself. For instance, reducing the amount of PI without impacting capacity demands in a WMC task raised WMC scores and reduced the correlation between WMC and recall of a prose passage (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999). Similarly, when using the Brown-Peterson task or paired-associate learning, the PI effect in recall totals was found to be increased for low-WMC individuals relative to high-WMC individuals (e.g., Friedman & Miyake, 2004; Kane & Engle, 2000).

Whereas on the basis of two-stage models of recall, the prior work on recall totals leaves it open whether WMC influences sampling processes, recovery processes, or both, other work suggests that WMC at least influences sampling processes (Unsworth, 2007, 2009; Unsworth & Engle, 2007). Unsworth and Engle (2007), for instance, found that when low WMC individuals recalled a previously studied item list, their response latencies were increased relative to high-WMC individuals, indicating that, during recall, low-WMC individuals may be less skilled in creating adequate context cues for previously studied target information and thus may use cues that include nontarget information. The finding is of direct relevance for PI, suggesting that it may be more difficult for low-WMC than high-WMC subjects to exclude the previously studied nontarget items from sampling and focus mental search at the most recent (target) list. If so, low-WMC individuals should show a more pronounced PI effect in response latencies than high-WMC individuals.

Finally, WMC may also play a role during target list encoding and, regarding PI, may influence the degree of impaired target list encoding. Behavioral work suggests that high-WMC individuals are better in strategic encoding processes (Unsworth & Spillers, 2010) and have superior attentional control (Unsworth, Spillers, & Brewer, 2009) than low-WMC subjects. Since, during multiple-list encoding, impaired target list encoding has been linked to increases in theta and alpha activities and such increases are supposed to reflect increased memory load and inattention (Pastötter et al., 2011; Sederberg et al., 2006), it may be expected that, in the PI task, the increase in electrophysiological activity across lists is less pronounced in high-WMC than low-WMC subjects.

The Present Study

The results of an EEG study are reported; the study was designed to examine the integrated encoding-retrieval account and the possible contribution of both encoding and retrieval processes to buildup of PI. Employing a typical PI task (e.g., Bäuml & Kliegl, 2013; Szpunar, McDermott, & Roediger, 2008; Unsworth et al., 2013), we examined the role of encoding processes by recording scalp EEG during study of nontarget and target lists, and we examined the role of retrieval processes by measuring recall totals and response latencies in target list recall. In addition, we measured subjects' WMC and examined to what degree WMC affects PI-related encoding and retrieval processes. Subjects studied a target list of unrelated items, and prior to target list encoding, studied three additional nontarget lists (PI condition) or performed an unrelated distractor task (no-PI condition). Following study of the target list and a subsequent distractor task, subjects were asked to recall as many target list items as possible. Finally, we assessed subjects' WMC employing two standard complex span tasks, the operation span task (Turner & Engle, 1989) and the reading span task (Daneman & Carpenter, 1980).

Several expectations arose. First, following the integrated encoding-retrieval account and temporal discrimination theory, we expected that the preceding nontarget list encoding created unfocused memory search during target list recall, inducing reactivation not only of target items but also of nontarget items. Reactivation of nontarget items should increase response latencies for target items and thus lead to higher latencies in the PI condition than in the no-PI condition (Bäuml & Kliegl, 2013; Wixted & Rohrer, 1993). If high-WMC individuals were better able than low-WMC individuals to restrict their memory search to the target items (Unsworth & Engle, 2007), then the increase in latencies in the PI condition relative to the no-PI condition should be smaller in high-WMC than low-WMC individuals.

Second, following the integrated encoding-retrieval account and prior EEG work on multiple-list learning, we expected the preceding encoding of the nontarget lists to increase memory load and inattention during target-list encoding and induce less complete memory representations for the target list items. Such impaired encoding should be reflected in higher electrophysiological activity in the theta and alpha frequency bands of the EEG (e.g., Pastötter et al., 2008, 2011) and induce a recovery problem at test, reducing recall totals in the PI condition. Because the increase in electrophysiological activities across lists has been attributed to problems in attention and memory load and because high-WMC individuals seem to be better able to control encoding processes (e.g., Unsworth & Spillers, 2010), high-WMC individuals may be expected to show a less pronounced increase in electrophysiological activity across lists than low-WMC individuals. If so, PI would be reflected in both impaired encoding and impaired retrieval processes, and both types of processes be related to subjects' WMC.

Method

Subjects

Seventy-two volunteers participated in the experiment. Four subjects had to be excluded from the sample because of an insufficient number of artifact-free trials in their EEG. Eight further subjects had to be excluded because they produced less than eight target list items in either the PI or no-PI condition, which made it impossible to obtain valid individual response latency estimates (see Recording and Analysis of Response Latencies below). The remaining sample consisted of 60 subjects (mean age = 22.5 years, range = 18–30 years, 46 females). All subjects spoke German as their native language and reported no neurological or psychiatric disease. All volunteers gave their written informed consent and received 25 Euros for participation.

Materials

As study material, 180 unrelated words of medium frequency were drawn from the CELEX database using the Wordgen v1.0 software toolbox (Duyck, Desmet, Verbeke, & Brysbaert, 2004). Eighteen items were assigned to each of 10 lists. For each partic-

ipant, the 10 lists were distributed across the two experimental conditions: eight lists were assigned to the PI condition and two lists were assigned to the no-PI condition. Across lists, words were matched on frequency and word length. Each list was used equally often in the PI and no-PI conditions.

Design and Procedure

The experiment was composed of two conditions: the PI condition and the no-PI condition. Each participant took part in both conditions. Subjects always studied a target list. Conditions differed with respect to what happened before target list encoding. In the PI condition, three preceding lists were studied, whereas in the no-PI condition, no preceding list was studied, but an unrelated distractor task was carried out.

All subjects were asked to study several item lists. Each participant took part in two successive experimental blocks, each block consisting of a PI and a no-PI condition. Order of the two conditions within each block was counterbalanced across subjects. Each of the conditions consisted of a learning phase, an intermediate phase, and a test phase. In the learning phase, subjects always studied a target list and prior to that were either exposed to three preceding nontarget lists (PI condition) or performed an unrelated distractor task. In the distractor task, 18 photographs depicting international celebrities were presented three times in a row, and in each round, subjects had 4,500 ms to rate a celebrity with respect to one specific attribute (attractiveness, likability, or trustworthiness; no-PI condition). The 18 words of each list were exposed individually for 2,500 ms, following a prestimulus interval of variable duration (1,800–2,200 ms), in which a fixation cross was shown. The items of each list were visually presented in the center of the computer screen. After presentation of each single list, subjects counted backward in steps of three for 30 sec from a random 3-digit number. EEG was recorded during encoding of the single lists. The intermediate phase was the same in every condition and served as a recency control. It lasted for 2 min and subjects were told to orally group blocks of five digits in an ascending order. Following the intermediate phase, subjects were given 1 min to orally recall as many items as possible from the target list in any order they wished. In the PI condition, the three nontarget lists were tested subsequently in a random order, but the results are not reported. Between the two experimental conditions of a block, there was a break of 1 min before the next condition started (see Figure 1). Between the two experimental blocks, there was a break of 2 min.

Recording and Analysis of Response Latencies

The subjects' answers at test were recorded by a computer program in a pcm-wav format with a sampling rate of 44.1 kHz and a resolution of 16 bit. Latencies were assessed by means of the computer program Cool Edit, 2000 (version 4.1, Syntrillium Software Corporation, Phoenix, AZ), whereby the voice onset of each recalled item was manually located in the spectrogram (see Bäuml & Kliegl, 2013; Bäuml, Zellner, & Vilimek, 2005).

Analysis of response latencies over a wide range of experiments has revealed that subjects typically remember many items early in the recall period and relatively few items later in the recall period. Consistently, response latencies have been found to be well described by means of an exponential,

$$r(t) = (N/\tau)e^{-t/\tau},$$

where $r(t)$ represents the number of items recalled at time t(or, in

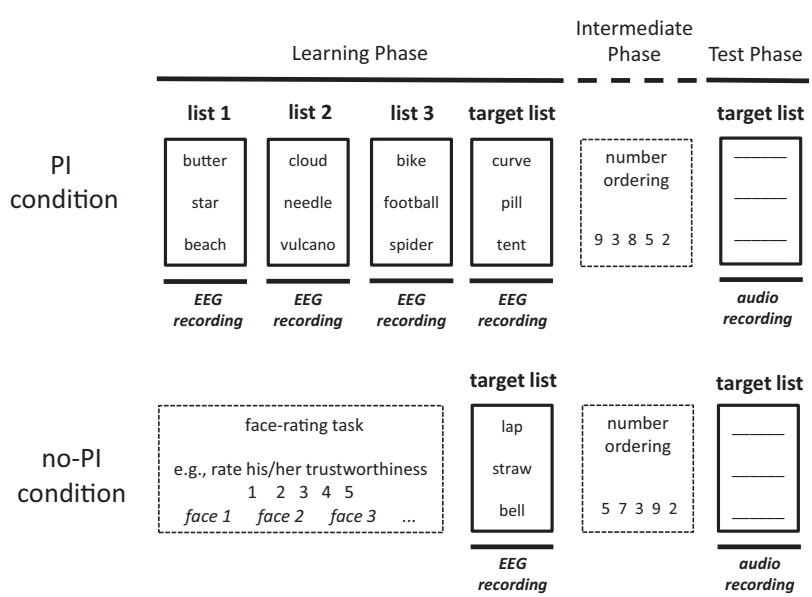

Figure 1. Depiction of the procedure. Subjects either studied three preceding (nontarget) lists (PI condition) or took part in a face rating task of equal duration (no-PI condition) before they studied the target list of items. At test, subjects in both conditions were told to recall as many target list items as possible. Subjects' EEG was recorded during encoding of the single lists and subjects' verbal responses were recorded during the recall period.

practice, at a particular time interval t), N represents asymptotic recall (the estimated number of items that could be produced given unlimited time), and τ represents the mean response latency of those N items (Bousfield & Sedgewick, 1944).

Prior work on response latency analysis often distinguished between first-response and subsequent-response latency (e.g., Bäuml et al., 2005; Rohrer, Wixted, Salmon, & Butters, 1995). First-response latency measures the average duration until the onset of the first recalled item and is thought to reflect the initiation of the search set; subsequent-response latency measures the duration between the first response and each subsequent response and is assumed to capture retrieval from the search set, therefore being a purer measure of the recall process itself (for a discussion, see Rohrer et al., 1995). Prior work reported evidence that the buildup of PI mainly affects the recall process itself and less, if at all, the initiation process (Bäuml & Kliegl, 2013; Wixted & Rohrer, 1993). On the basis of these findings it may be expected that buildup of PI is mostly reflected in subjects' subsequent-response latencies and less, if at all, in their first-response latencies.

First-response latencies and subsequent-response latencies of the target list were analyzed for both the PI condition and the no-PI condition. Exponential functions were fitted to the subsequent-response latency functions of each individual participant and of each condition in order to analyze retrieval dynamics. Two parameters describe those functions—N representing asymptotic recall and τ representing the mean latency of those N items—which were derived from fitting the exponential to the data. The best fitting exponentials were determined by least square minimization (for details, see Rohrer et al., 1995). Subjects who recalled less than eight target list items in either the PI or no-PI conditions across the two experimental blocks were excluded from the sample because no valid estimates of individual subsequent-response latencies could be obtained (see Subjects above).

Working Memory Tasks

Two working memory tasks were administered one day subsequent to the PI experiment. Subjects' WMC was assessed with German versions of the operation span (Ospan) task (Turner & Engle, 1989; see also Aslan & Bäuml, 2011, or Aslan, Zellner, & Bäuml, 2010) and the reading span (Rspan) task (Daneman & Carpenter, 1980).

The Ospan task required subjects to solve arithmetic equations while trying to remember unrelated words. Each trial consisted of a certain number (varying between 2 and 6) of successively presented equation-word pairs, for example, *(8 + 4) + 3 = 5? moon*. Subjects read each equation aloud, verified whether it was correct by saying "yes" or "no," and read the to-be-remembered word (moon) aloud. The Rspan task required subjects to read sentences aloud while trying to remember the last word of each sentence. Each trial consisted of a certain number (varying between 2 and 6) of successively presented sentences, for example, "When at last his eyes opened, there was no gleam of triumph, no shade of anger." At the end of each sentence, subjects verified whether the sentence makes sense by saying "yes" or "no."

In both tasks, subjects were urged to respond quickly. Immediately after each response, the next equation—word pair or sentence was presented. Following the last equation-word pair or sentence, subjects were asked to recall the to-be-remembered words in correct order. There were three repetitions of each set size (2–6), leading to a maximum score of 60 in each of the two tasks. In both WMC tasks, the span score was defined as the sum of correctly recalled words across trials (Turner & Engle, 1989; see Conway et al., 2005, for a review of scoring methods). The arithmetic mean of the two tasks was used as our composite WMC score.

EEG Recording

During list encoding, EEG was recorded from 61 electrodes mounted in an elastic cap (ActiCAP, Montage 10, Brain Products, Gilching, Germany). Electrode—skin impedance was kept below 20 kΩ. Electrode Cz served as the common reference. Signals were digitalized with a sampling rate of 500 Hz and amplified between 0.15 and 100 Hz with a notch filter at 50 Hz to remove line noise (BrainAmpMR plus, BrainVision Recorder, Brain Products, Gilching, Germany).

EEG Processing

EEG recordings were offline-rereferenced against average reference and were EOG-corrected using calibration data to generate individual artifact coefficients (Ille, Berg, & Scherg, 2002) as implemented in the software package BESA (Brain Electrical Source Analysis, MEGIS Software v6.0, Gräfelfing, Germany). Remaining artifacts were marked by careful visual inspection.

As implemented in BESA (see Hoechstetter et al., 2004), each subject's EEG was transformed into the time-frequency domain using a complex demodulation algorithm (Papp & Ktonas, 1977). This algorithm consists of a multiplication of the time-domain signal with a complex periodic exponential function, with a frequency equal to the frequency under analysis, and a subsequent low-pass filter. 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 a frequency range from 2 to 20 Hz. Time resolution was set to 78.8 ms (full power width at half maximum, or FWHM), and frequency resolution was set to 1.42 Hz (FWHM). Time-frequency data were exported in bins of 50 ms and 1 Hz. Power spectral density was computed for each item presentation and was then averaged across artifact-free trials for each subject in each item list.

We examined stimulus-induced power changes by calculating the percentage of power decrease or power increase in relation to a prestimulus baseline interval (Pfurtscheller & Aranibar, 1977), which was set in the middle of the prestimulus interval, from 1,250 ms to 750 ms prior to stimulus onset. For statistical analysis, power data were collapsed in order to obtain two frequency bands (theta: 5–8 Hz, alpha: 10–13 Hz) and 10 time windows of 250 ms each from word onset (0 ms) to word offset (2,500 ms).

EEG Analysis

To examine whether electrophysiological activity is affected by amount of prior encoding, we calculated an index of subjects' mean power increase from encoding of List 1 to the target list in the PI condition. To this end, the change in power (P) with respect to list (L) was fitted to P(L) = bL + a, so that estimates of the regression coefficient (b) could be obtained. This was done for the theta (5–8 Hz) and alpha (10–13 Hz) frequency bands (2), for each time window (10), and electrode site (61). To account for multiple testing, a two-stage randomization procedure was carried out. At first, Wilcoxon's sign-rank tests were calculated for each electrode in order to investigate which electrodes showed a significant power increase ($p < .05$). Thereafter, a randomization test using 2,000 permutations was run in which we shuffled the order of the four lists consistently across electrodes (see Blair & Karniski, 1993). Comparable procedures had already been applied in several other studies from our lab (see, e.g., Hanslmayr, Spitzer, & Bäuml, 2009; Pastötter et al., 2008, 2011). The procedure evaluates whether a given number of electrodes, exhibiting a significant increase from nontarget to target-list encoding, is expected by chance. If the p value (p_{corr}) of this randomization test was below .05, then less than 5% of the permutation runs exhibited equal or more electrode sites with a significant power increase. If we found an effect to persist for two (or more) consecutive time windows (e.g., from 250 ms to 500 ms and from 500 ms to 750 ms), then we ran a new randomization test for the expanded time window of interest (e.g., from 250 ms to 750 ms; for a similar procedure, see Pastötter et al., 2011). Across significant electrode sites, we then examined the time course of stimulus-induced power changes in the theta and alpha bands and the relationship between power effects and behavior by calculating Spearman correlational coefficients between the regression coefficient (b) and the PI effect in recall totals and response latencies. Finally, we examined theta and alpha power changes from encoding of list 1 to the target list in the PI conditions as a function of individuals' WMC.[2]

Results

Table 1 shows descriptive statistics for all memory measures. As can be seen from the table, all of the measures were approximately normally distributed, with all values of skewness and kurtosis falling under the generally accepted critical values of 2 for skewness and 4 for kurtosis (see Kline, 1998). The reliabilities for the difference-score measures of response totals and response latencies in the PI task [that is, PI effect (totals), PI effect (latencies)] were lower than those for the single-score measures and the WMC task, a pattern that mirrors the results of previous studies (Friedman & Miyake, 2004; Unsworth, 2010).

Behavioral Results

Regarding recall totals, subjects correctly recalled 60.0% of the target items in the no-PI condition and 47.1% in the PI condition. The difference of 12.9% was reliable, $t(59) = 7.072$, $p < .001$, $d = 1.841$, illustrating the buildup of PI from the no-PI to the PI condition (Figure 2A, left panel).

Table 1
Descriptive Statistics and Reliability Estimates for the Working Memory Capacity (WMC) Task (Measure 1) and The Proactive Interference (PI) Task (Measures 2–9)

Measure	*M*	*SD*	Skew	Kurtosis	Reliability
1. WMC	43.57	6.00	0.24	0.02	0.73
2. Target list totals (PI)	47.18	18.35	0.38	−0.68	0.75
3. Target list totals (no PI)	59.91	15.75	0.05	−0.82	0.81
4. PI effect (totals)	12.73	14.34	0.35	0.09	0.38
5. Target list latencies (PI)	12.44	6.21	0.93	0.93	0.59
6. Target list latencies (no PI)	10.82	5.65	0.66	0.20	0.79
7. PI effect (latencies)	1.65	6.07	1.78	3.77	0.31
8. Theta increase	2.41	6.02	−0.68	2.92	—
9. Alpha increase	2.61	4.97	0.32	0.03	—

Note. WMC = composite working memory capacity score; totals = recall totals (in %); PI = PI condition; no PI = no-PI condition; PI effect (totals) = target list totals (no PI)–target list totals (PI); latencies = response latencies (in seconds); PI effect (latencies) = target list latencies (PI)–target list latencies (no PI); theta/alpha increase: mean list-to-list increase (in %) in theta/alpha power from encoding of the three nontarget lists to encoding of the target list. For the seven behavioral measures, reliability was calculated using Cronbach's alpha. For the two EEG measures, no reliability estimates are reported. Here, to get sufficiently high statistical power, the data from the two experimental blocks had to be pooled and no independent estimates for each block and subject could be deduced.

Regarding response latencies, first-response latencies were 1.8 s in the no-PI condition and 2.1 s in the PI condition. The difference of 0.3 s was not significant, $t(59) = 1.329$, $p = .186$, suggesting that first-response latencies did not depend on condition. Subsequent-response latencies were grouped in 5-s bins and a two-parameter exponential was fitted to the data points of each single participant. Figure 2C exemplarily shows the response latency distribution of two typical subjects with the best-fitting exponential functions for the PI and no-PI conditions. On average, the exponential accounted for 77.8% of the variance in the PI condition and 85.3% in the no-PI condition. The mean parameter estimate of asymptotic total (N) revealed values of 43.9% for target list recall in the PI condition and 55.3% for target list recall in the no-PI condition. N is based on subsequent responses only, whereas recall totals include first responses as well. Corrected totals, in which only the subsequent responses were included—41.5% in the PI condition and 54.4% in the no-PI condition—were very similar to the estimated values of N, indicating that recall was close to asymptote in both conditions. The main focus in this study was on mean subsequent-response latency (τ), however. The mean τ parameter estimates were 12.4 s for the PI condition and 10.8 s for the no-PI condition. The difference of 1.6 s between the two conditions was reliable, $t(59) = 2.068$, $p = .043$, $d = .538$ (Figure 2B, left panel), demonstrating that buildup of PI was

[2] Note that, a priori, we also analyzed indices of subjects' mean power increases from list 1 to target list encoding in the PI condition in the delta (2–4 Hz) and lower beta (15–20 Hz) frequency bands. However, for these bands, results showed no significant power increases across lists, all $ps_{corr} > .50$. We did not analyze potential power changes in higher frequency ranges (>20 Hz) and also did not analyze subsequent-memory effects in the theta and alpha frequency bands. Such analyses would have required larger data sets than we employed in the present study.

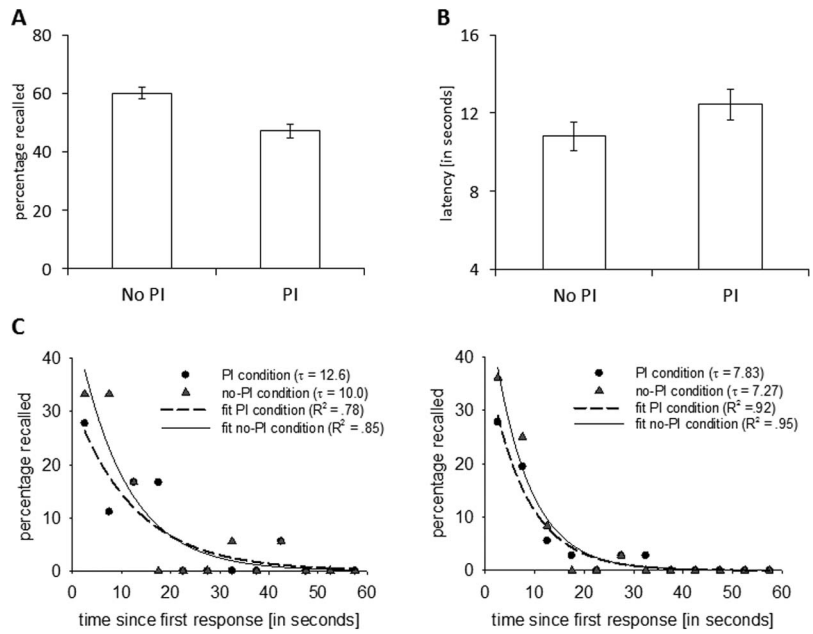

Figure 2. Behavioral results. (A) Mean recall totals for target list items; error bars represent standard errors. (B) Mean response latencies for target list items; error bars represent standard errors. (C) Response latency distributions and best-fitting exponential functions for the PI and no-PI conditions shown exemplarily for two typical subjects: recall was slower in the PI than the no-PI condition, as is also reflected in the τ estimates.

reflected in response latencies. The individual PI effects in response latencies and recall totals were uncorrelated, $r = -.09$, $p = .495$.[3]

Physiological Results

Regarding theta power (5–8 Hz), red areas in Figure 3A depict scalp topographies exhibiting significant increases in stimulus-induced theta power from encoding of list 1 to encoding of the target list in the PI condition, illustrating that theta power increased across widespread areas over the scalp. Randomization tests, which evaluate whether theta-power changes from list 1 to the target list would be expected by chance, showed a significant increase in the theta band 750 ms to 1,250 ms after stimulus onset, $p_{corr} < .01$. On the basis of the electrodes that exhibited a significant theta increase, Figure 3B depicts the time course of theta power for (a) List 1, (b) the target list in the PI condition, and (c) the target list in the no-PI condition. Theta power in the PI condition was significantly increased for the target list, both relative to list 1, $t(59) = 2.487$, $p = .016$, $d = .647$, and relative to the target list in the no-PI condition, $t(59) = 2.092$, $p = .041$, $d = .541$, suggesting a reliable PI effect in the theta frequency band. There was no difference in theta power between List 1 in the PI condition and the target list in the no-PI condition, $t(59) < 1$ (see Figure 3C).

To investigate whether the increase in theta power across the four lists in the PI condition was related to the behavioral PI measures, we correlated individual theta regression coefficients and individual PI recall total scores. Theta regression coefficients estimated, for each participant, the linear increase in theta power across the four lists in the PI condition, and individual PI recall total scores were calculated by subtracting for each participant the percentage of correctly recalled target items in the PI condition from the percentage of correctly recalled items in the no-PI condition. We found a positive relationship between the two measures, $r = .27$, $p = .040$, indicating that high increases in theta power were accompanied by high levels of PI in recall totals. We also determined individual PI response latency scores, which were calculated by subtracting for each participant the estimated latency for target list recall in the no-PI condition from the estimated latency for target list recall in the PI condition. There was no significant correlation between individual theta regression scores and individual PI response latency scores, $r = .11$, $p = .408$.

Regarding alpha power (10–13 Hz), red areas in Figure 3D depict scalp topographies exhibiting significant increases in

[3] To examine the robustness of the latency findings, we ran two additional analyses. As the first analysis, we estimated response latencies by fitting the exponential to individual response latency distributions that were split out by the total number of items recalled in each list by each individual participant. Naturally, employing this estimation method, N estimates were 1.0 in both the PI and the no-PI condition. More important, τ parameter estimates were largely unaffected and there was again a reliable difference between the PI condition (mean τ estimate = 12.4 s) and the no-PI condition (mean τ estimate = 10.8 s), $t(59) = 2.068$, $p = .043$, $d = .538$. As the second analysis, we estimated response latencies only for those subjects whose exponential fit to their individual response latency distributions accounted for at least 75% of the variance in both the PI and no-PI conditions. Consistent with the results reported above, there was again a reliable difference in mean τ parameter estimates between the PI condition (mean τ estimate = 11.1 s) and the no-PI condition (mean τ estimate = 9.9 s), $t(33) = 2.192$, $p = .036$, $d = .763$.

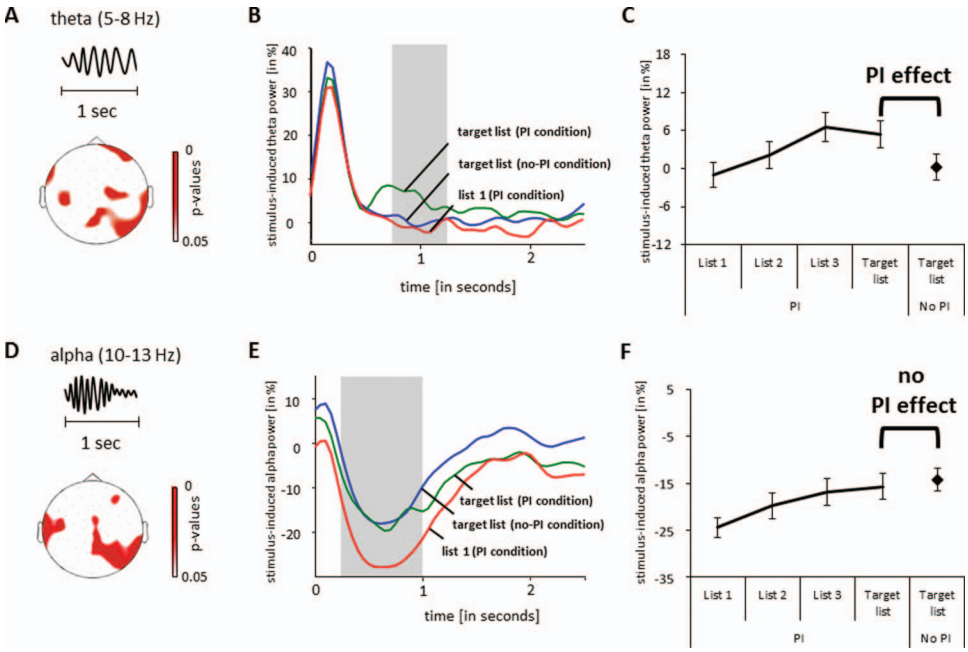

Figure 3. Physiological results. Theta (5–8 Hz) and alpha power (10–13 Hz). (A, D) Scalp topographies depict the electrodes that exhibited significant increases in theta (5–8 Hz, 750 to 1,250 ms, upper row) and alpha power (10–13 Hz, 250 to 1,000 ms, lower row) from encoding of the nontarget lists to the target list in the PI condition. Red (black) areas denote an increase in theta power. No electrode showed a decrease in theta power (B, E). Time courses of theta (upper row) and alpha power (lower row) for List 1, the target list in the PI condition, and the target list in the no-PI condition. For theta power, time courses are depicted for those electrodes that showed a significant increase in theta power from nontarget to target list encoding during the time window of 750 to 1,250 ms following stimulus onset; for alpha power, time courses are depicted for those electrodes that showed a significant increase in alpha power from nontarget to target list encoding during the time window of 250 to 1,000 ms following stimulus onset (C, F). Theta (upper row) and alpha power (lower row) for the target list in the PI and no-PI conditions and the three nontarget lists in the PI condition, averaged across their respective time windows. The color version of this figure appears in the online article only.

stimulus-induced alpha power from List 1 to the target list, illustrating that alpha power increased across widespread areas over the scalp. Randomization tests, which evaluate whether alpha-power changes from List 1 to the target list would be expected by chance, showed a significant increase in the alpha band 250 ms to 1,000 ms after stimulus onset, $p_{corr} < .01$. On the basis of those electrodes that exhibited a significant alpha increase, Figure 3E depicts the time course of alpha power for List 1 and the target lists in the PI and no-PI conditions. There was a significant increase both from List 1 to the target list in the PI condition, $t(59) = 3.778$, $p < .001$, $d = .984$, and from List 1 to the target list in the no-PI condition, $t(59) = 4.656$, $p < .001$, $d = 1.212$ (see Figure 3F). In contrast, there was no difference between target lists in the PI and no-PI conditions, $t(59) < 1$. These findings indicate that the increase in alpha power was not related to the preceding encoding of the nontarget lists but rather reflects a more general, not PI-related physiological effect.

Working Memory Capacity

Subjects' mean Ospan score was 49.4 ($SD = 5.3$, range 36–59) and subjects' mean Rspan score was 37.8 ($SD = 7.9$, range 23–58). To examine the relationship between WMC and measures of our PI task, we followed the prior WMC work and employed the arithmetic mean of the two scores (see Table 1).

In the first step, we examined whether individuals' WMC affects recall performance of a single list with respect to both recall totals and response latencies. We found significant correlations both between WMC and target list recall totals in the no-PI condition, $r = .52$, $p < .001$, and between WMC and target list τ estimates in the no-PI condition, $r = .33$, $p = .010$. Regarding the relationship between WMC and PI, we found no significant correlation between WMC and amount of PI in recall totals, $r = -.07$, $p = .589$, but a reliable correlation between WMC and amount of PI in response latencies, $r = -.33$, $p = .010$, suggesting that the PI effect in latencies, but not the PI effect in recall totals, was significantly affected by individuals' WMC.

In the second step, we examined whether WMC modulated the theta and alpha power increase during encoding of the four lists in the PI condition. We found a negative correlation between WMC and theta regression coefficients, $r = -.33$, $p = .011$, but found no reliable correlation between WMC and alpha regression coefficients, $r = -.14$, $p = .275$. The finding suggests that the increase in theta power, but not the increase in alpha power, was modulated

by individuals' WMC, with low-WMC individuals showing a more pronounced increase in theta power across lists than high-WMC individuals.

Discussion

Retrieval Factors

Consistent with prior work on buildup of PI, the results of the present study show that recall of a target list is impaired by the preceding study of nontarget lists, relative to a control condition in which an unrelated task is performed prior to target list encoding. The PI effect arose in recall totals and response latencies, suggesting that the prior nontarget encoding does not only reduce number of recalled target items but additionally slows the retrieval process (Bäuml & Kliegl, 2013; Unsworth, Brewer, & Spillers, 2013; Wixted & Rohrer, 1993). The PI effects in recall totals and response latencies were uncorrelated. This finding is consistent with the results of previous studies, which suggested that recall totals and response latencies can be functionally independent (e.g., Bäuml et al., 2005; Rohrer, Salmon, Wixted, & Paulsen, 1999; Rohrer & Wixted, 1994; Wixted & Rohrer, 1994),[4] and supports two-stage models of recall, which assume that recall totals and response latencies can provide windows into different stages of the retrieval process (e.g., Raaijmakers & Shiffrin, 1981; Rohrer, 1996). Accordingly, the increase in response latencies in the PI condition suggests a problem at the sampling stage of recall after prior nontarget encoding. Mental search at the sampling stage appears to be less focused in the presence than in the absence of nontarget material, thus increasing breadth of search and increasing response latencies for the target items (e.g., Wixted & Rohrer, 1993). The PI effect in recall totals points to an additional problem at the recovery stage of recall.

Encoding Factors

Analysis of electrophysiological activities during list encoding indicates that not only retrieval but also encoding can contribute to buildup of PI. Electrophysiological activities in the theta and alpha bands were found to increase from nontarget to target list encoding, indicating that in the presence of nontarget lists, target encoding can suffer from inattention and increased memory load (Palva & Palva, 2007; Pastötter et al., 2008, 2011; Sederberg et al., 2006). When relating increases in electrophysiological activities in the two frequency bands to buildup of PI, and thus comparing oscillatory activity for the target list in the PI condition with oscillatory activity for the target list in the no-PI condition, however, we found theta power, but not alpha power, to be increased in the PI condition. This finding suggests that mainly theta activity, and to a lesser extent alpha activity, may serve as an encoding correlate of PI buildup. If alpha activity captured mainly attentional processes (Klimesch, 2012; Palva & Palva, 2007) and theta activity mainly memory load (Jensen & Tesche, 2002; Onton et al., 2005), then the present results suggest that the PI-related encoding problem may reflect primarily a memory load problem. Such a problem, for instance, may arise from generally deteriorated buffer operations in a limited working memory capacity rehearsal buffer (Lehman & Malmberg, 2011), or from memory reactivation and competition of previously encoded nontarget items, which may impair encoding of the target items (Lundqvist, Herman, & Lansner, 2011).

The present increase in alpha activity from nontarget to target list encoding is consistent with the results of a recent study employing multiple-list learning (Pastötter et al., 2011). This study reported that during successive encoding of 5-item lists, a reliable increase in alpha activity from encoding of List 1 to encoding of List 5 arose, and such increase was negatively correlated with recall of List-5 items. While the present study replicates this finding,[5] it goes beyond this recent work by showing that the effect in alpha activity may not be PI-related, and increased alpha activity also arises after conducting tasks unlikely to induce PI, for example, rating celebrities with respect to different traits (see Method section above). Thus, whereas oscillatory theta power may serve as an encoding index of PI buildup, the present effect in oscillatory alpha power may reflect an unspecific reduction in attentional processes that can arise for PI-related and PI-unrelated tasks.[6]

Fit With the Integrated Encoding-Retrieval Account

The present results are in line with the suggested integrated encoding-retrieval account of PI, according to which both encoding and retrieval factors contribute to buildup of PI. The account assumes that the prior study of nontarget material causes a discrimination problem for target items during the sampling stage of recall, and the present finding of a PI effect in response latencies is consistent with this view. In addition, the account assumes that the encoding of target list items can be impaired through the preceding encoding of nontarget items, which may lead to more incomplete memory representation for the target items and may prevent the items from exceeding the recall threshold during the recovery stage of recall. The finding of PI-specific increased theta activities after prior nontarget encoding indeed points to impaired target list encoding. Moreover, the fact that the increase in theta activity was positively correlated with the PI effect in recall totals, but not in response latencies, suggests that the impaired encoding induced primarily a recovery problem, and much less, if at all, a sampling problem at recall.

[4] The indication that recall totals and response latencies can be functionally independent does not imply that the two measures should be expected to be unrelated under all circumstances. Rather, in prior work, the two measures have been found to be either positively related, negatively related, or unrelated (e.g., Rohrer, Salmon, Wixted, & Paulsen, 1999; Unsworth, 2009; Wixted, Ghadisha, & Vera, 1997), suggesting that the circumstances that surround an experimental situation determine the relationship between latencies and recall totals.

[5] Pastötter, Schicker, Niedernhuber, and Bäuml (2011) reported a negative correlation between the alpha power increase—from List-1 to List-5 encoding—and List-5 recall totals, $r = -.47$, $p = .050$. Similarly, in the present study, we found a negative correlation between the alpha power increase—from (nontarget) List-1 to (target) List-4 encoding—and (target) List-4 recall totals, $r = -.27$, $p = .034$.

[6] The present study employed a completely within-subjects design. As a result, there is no true no-PI condition, because in many cases the no-PI trials were preceded by PI trials (and other no-PI trials). Arguably, this design issue could be responsible for not finding a PI effect in alpha activity in the present study. While our results cannot rule out this possibility, the finding of a PI effect in response latencies, in recall totals, and particularly in theta activity clearly challenges such view, indicating that the influence of unspecific PI in the present study was probably quite limited.

Previous accounts of PI attributed the source of PI to either encoding or retrieval factors. The present results, which include both behavioral and neural measures of PI, together with the suggested integrated account, assign a role for both encoding and retrieval factors in buildup of PI, and indicate that both factors may contribute to buildup of PI. While the present results are thus consistent with the suggested account, further work should be conducted to examine the adequacy of the account in more detail. For instance, although the present latency findings are in line with the view that search set size is larger in the PI than no-PI condition and sampling problems contribute to PI (e.g., Bäuml & Kliegl, 2013; Unsworth et al., 2013; Wixted & Rohrer, 1993), on its own the present results cannot rule out that the differences in latencies may be due to encoding differences. Following Burns and Schoff (1998), for instance, the prior nontarget encoding in the PI condition may have caused subjects to use different processing strategies during target list encoding, which may have been more demanding at retrieval, thereby slowing the recall process (but see Bäuml & Kliegl, 2013). Similarly, although the present theta findings are in line with the view that memory load is increased during target list encoding in the PI relative to the no-PI condition and the increased load impairs encoding and thus reduces recall totals (e.g., Pastötter et al., 2008; Sederberg et al., 2006), on its own the present results cannot rule out that in the present situation theta wave differences may have resulted from factors other than encoding deficits, like different kinds of encoding processes or strategies. Thus, although the conclusions drawn in the present study are in line with the present results and are reasonably bolstered by the findings of many previous studies, we await further research examining the present proposal.

The Role of Working Memory Capacity for Proactive Interference

The present results show that the degree to which PI-related retrieval and encoding problems arise depends on subjects' WMC. Regarding retrieval, we found that WMC modulates the PI effect in latencies, with low-WMC individuals exhibiting a slower recall process after prior nontarget encoding than high-WMC individuals. Because the WMC-induced effect in latencies indicates that the prior nontarget encoding increased the mental search set mainly for low-WMC individuals and less for high-WMC individuals, the findings indicate that low-WMC individuals employed less focused retrieval cues to delimit the mental search set size and thus included more nontarget items in the search set than high-WMC subjects. These findings are consistent with the general view that low-WMC and high-WMC individuals differ with respect to their ability to use appropriate retrieval cues to refine their mental search for target items (Unsworth & Engle, 2007).

Subjects' WMC did not only affect PI-related retrieval but also PI-related encoding processes. In fact, the increase in theta power across lists in the PI condition was more pronounced in low-WMC than high-WMC individuals. This finding suggests that high-WMC individuals suffer less from memory load problems during encoding and are better able than low-WMC subjects to separate the currently to-be-encoded (target) items from the previously encoded (nontarget) material. If so, high WMC may reduce PI by generally permitting better focus on the target material at both encoding and retrieval.

Although the present WMC findings broadly fit with prior work on WMC and PI, there are two aspects in the results that contrast with the prior work. The first aspect is that previous studies reported a reduced PI effect in recall totals for high-WMC subjects relative to low-WMC subjects (Friedman & Miyake, 2004; Kane & Engle, 2000; Unsworth, 2010), whereas in the present study no significant effect of WMC arose. However, the difference between the present and the prior work may be more quantitative than qualitative in nature. For instance, Unsworth (2010) reported (significant) negative correlations of −.13 and −.30 between the PI effect in recall totals and the Ospan and Rspan measures of WMC, whereas in the present study, we found (nonsignificant) correlations of −.16 and −.04 between the PI effect in totals and the Ospan and Rspan measures of WMC. While all of these correlations thus show a similar tendency, it remains unclear, of course, why we did not find a more pronounced relationship in our study. One possibility could be that the role of WMC for PI varies with PI task and, for instance, is larger in paired associate learning and the Brown-Peterson task, which were used in the previous studies, than it is in list learning, which was used in the present study.

The second aspect in the results that contrasts with prior work is that previous studies found that low-WMC individuals' recall of a single list can be slower than high-WMC individuals' recall (Unsworth, 2007, 2009; Unsworth & Engle, 2007), whereas in the present study the reversed picture arose. Unsworth and colleagues argued that during recall, low-WMC individuals may be less skilled in creating adequate context cues for previously studied target information and thus may use cues that include nontarget information, which may slow the recall process. Alternatively, however, if high-WMC subjects used more strategic processing during item encoding than low-WMC subjects (e.g., Unsworth & Spillers, 2010) and such strategic processing increased the number of sampled items, then high-WMC subjects may show increased latencies relative to the low-WMC subjects. Such differential encoding between high- and low-WMC subjects may have played a reduced role in the Unsworth et al. studies, because, in this prior work, item presentation rate was faster than in the present study (1 sec vs. 5 sec), likely leaving less room for strategic encoding even for high-WMC subjects. Further factors may influence latencies of low- and high-WMC subjects differently, like number of recalled items (e.g., Wixted, Ghadisha, & Vera, 1997) or recall termination processes (Miller, Weidemann, & Kahana, 2012), making it difficult to evaluate exactly which factor(s) caused the difference in results between studies. Future work may provide new insights into the issue by simultaneously examining the influence of several of these factors on the response latencies of low- and high-WMC subjects.

On a final note we would like to emphasize that, although the present study was reasonably powered for the PI questions and EEG issues that were addressed in this study, it was somewhat underpowered for individual differences issues. As a result, some of the small and nonsignificant correlations reported in the present study, that is, the nonsignificant relation between WMC and the PI effect in recall totals, may be due to the relatively low reliability of the difference scores we employed in our PI task. Hence, further studies may like to revisit some of the current issues using higher statistical power than we were able to employ in the present study. Such work may further improve our understanding of encoding and retrieval processes in PI.

Conclusions

Employing behavioral and neural measures of PI, this study showed that both impaired encoding and impaired retrieval can contribute to buildup of PI. Whereas the prior study of nontarget lists can impair target list encoding due to increased memory load, it impairs retrieval of target items due to reduced temporal discrimination at sampling. These findings are consistent with an integrated encoding-retrieval account, which assigns a role for both encoding and retrieval processes in buildup of PI. For both types of processes, PI was reduced in high-WMC subjects, suggesting that these subjects can reduce PI by separating target from nontarget information and creating stronger focus on the target material, both at encoding and retrieval.

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