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The cost of proactive interference is constant across presentation conditions

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Abstract

Proactive interference (PI) severely constrains how many items people can remember. For example, Endress and Potter (2014a) presented participants with sequences of everyday objects at 250ms/picture, followed by a yes/no recognition test. They manipulated PI by either using new images on every trial in the unique condition (thus minimizing PI among items), or by re-using images from a limited pool for all trials in the repeated condition (thus maximizing PI among items). In the low-PI unique condition, the probability of remembering an item was essentially independent of the number of memory items, showing no clear memory limitations; more traditional working memory-like memory limitations appeared only in the high-PI repeated condition. Here, we ask whether the effects of PI are modulated by the availability of long-term memory (LTM) and verbal resources. Participants viewed sequences of 21 images, followed by a yes/no recognition test. Items were presented either quickly (250ms/image) or sufficiently slowly (1500ms/image) to produce LTM representations, either with or without verbal suppression. Across conditions, participants performed better in the unique than in the repeated condition, and better for slow than for fast presentations. In contrast, verbal suppression impaired performance only with slow presentations. The relative cost of PI was remarkably constant across conditions: Relative to the unique condition, performance in the repeated condition was about 15% lower in all conditions. The cost of PI thus seems to be a function of the relative strength or recency of target items and interfering items, but relatively insensitive to other experimental manipulations.

The cost of proactive interference is constant across presentation conditions

Introduction

Proactive interference (PI) occurs when the retrieval of a stimulus is impaired due to previously experiencing similar stimuli. It has long been known to limit how many items we can remember over the short term (see, among many others, e.g., Baddeley & Scott, 1971; Berman, Jonides, & Lewis, 2009; Cowan, Johnson, & Saults, 2005; Endress & Potter, 2014a; Keppel & Underwood, 1962; Kincaid & Wickens, 1970; Lewandowsky, Oberauer, & Brown, 2009; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999; Makovski & Jiang, 2008; Wickens, Born, & Allen, 1963) and over the long term (e.g., Baddeley, 1966; da Costa Pinto & Baddeley, 1991; Ericsson & Kintsch, 1995). It might also contribute to one of the classic memory limitations, namely those of Working Memory (WM). WM is a temporary memory store where we can store items for on-going cognitive operations. It has a limited capacity (e.g., Awh, Barton, & Vogel, 2007; Luck & Vogel, 1997; Miller, 1956; Cowan, 2005; Rouder et al., 2008; W. Zhang & Luck, 2008) or a limited precision (e.g., Alvarez & Cavanagh, 2004; Bays & Husain, 2008; Bays, Catalao, & Husain, 2009; van den Berg, Shin, Chou, George, & Ma, 2012). Some authors have suggested that its function is to counteract the effects of PI (e.g., Engle, 2002). Accordingly, there are interference-based computational models of even the most complex WM tasks — complex span tasks (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). Indeed, WM capacity as measured by complex span tasks correlates with susceptibility to interference (e.g., Conway & Engle, 1994; Conway, Kane, & Engle, 2003; Kane & Engle, 2000, 2003; May et al., 1999; Rosen & Engle, 1998), and both WM capacity and susceptibility to interference correlate with IQ (e.g., Braver, Gray, & Burgess, 2008; Burgess, Gray, Conway, & Braver, 2011; Conway et al., 2003; Engle, Tuholski, Laughlin, & Conway, 1999; Fukuda, Vogel, Mayr, & Awh, 2010; Gray, Chabris, & Braver, 2003; Kane et al., 2004). Further, brain imaging studies have shown that the prefrontal regions that are generally linked to control functions in WM tasks are also activated by PI, and, in fact, memory tasks that minimize PI do not seem to recruit these regions (e.g., Hasselmo & Stern, 2006; Ranganath & D'Esposito, 2001;

Ranganath & Rainer, 2003; Stern, Sherman, Kirchhoff, & Hasselmo, 2001).

Here, we investigate the cost of PI under different presentation conditions. This question is important because the types of mechanisms we use to remember items over the short-term are not unitary, and show contributions from visual, conceptual, linguistic, and attentional processes, among others (e.g., Baddeley & Hitch, 1974; Baddeley, 1996, 2003; Cowan, 1995, 2001, 2005; Endress & Potter, 2012; Feigenson & Halberda, 2008; Kibbe & Feigenson, 2014; Olsson & Poom, 2005; Potter, 1976, 1993; Potter, Kroll, Yachzel, Carpenter, & Sherman, 1986; Rosenberg & Feigenson, 2013; Wong, Peterson, & Thompson, 2008; Wood, 2008). Further, at least according to some prominent theories of WM (e.g., Cowan, 2001), the storage function of WM is fulfilled by long-term memory (LTM; though recent research casts doubt on whether LTM is really distinct from more short-lasting forms of memory; see Ranganath & Blumenfeld, 2005, for a review).

Given that PI emerges in a variety of situations, and that it acts on many different processes and memory stores, the effects of PI might well be different in different situations. Here, we start investigating this issue by testing two components of memory: the availability of verbal memory, and the availability of LTM. We take advantage of a recent paradigm that showed virtually no memory limitations over the short-term when PI was minimized, but that revealed more traditional capacity limitations in the presence of strong PI among items (Endress & Potter, 2014a). Specifically, these authors presented adult participants with sequences of everyday pictures (taken from Brady, Konkle, Alvarez, & Oliva, 2008) in rapid sequential visual presentation (RSVP) at a presentation rate of 4 Hz, followed by a yes/no recognition test. Results showed that, as long as memory items were never repeated across trials (hereafter the unique condition), the proportion of remembered items, while well below ceiling, was essentially independent of the number of sequence items: the longer the sequence, the more items participants remembered (see Banta Lavenex, Boujon, Ndarugendamwo, & Lavenex, 2015, for similar results). In terms of memory capacities, participants thus did not show any clear capacity limitations. In contrast, when a limited set of items was reused across trials (hereafter the repeated condition), more traditional capacity limitations were observed. As repeating items across trials likely creates PI among items, PI limited the number of retrievable items. In fact, such PI is present in most WM experiments, as memory items are typically sampled from a limited set of items that are, therefore, repeated across trials. For example, in Luck and Vogel's (1997) change detection experiment, just 7 colors were re-used in hundreds of trials, which, in turn, might have led to substantial PI across trials. Hence, PI might have limited WM capacity estimates also in previous studies of visual WM (but see Hartshorne (2008); Lin and Luck (2012); Makovski and Jiang (2008), for opposing views, and Endress and Potter (2014a), for discussion).

In the experiment below, we keep "Temporary Memory" as a label for the short-lived memory investigated here. While WM capacity estimates might have been limited by PI in many WM experiments, we believe that the relationship between Temporary Memory and WM is an open issue, especially for the varieties of WM investigated in complex span tasks.

We build on Endress and Potter's (2014a) work, and ask how the cost of PI depends on the availability of verbal processes and of LTM. To manipulate the availability of verbal resources, participants did or did not complete a verbal suppression task simultaneously with the memory task. The manipulation of the availability of LTM relies on Endress and Potter's (2014a) and Endress and Potter's (2014b) experiments. In some of Endress and Potter's (2014a) experiments, participants completed a surprise LTM test at the end of the experiment; the retention delay was about half an hour. Results showed virtually no retention of the unique items, suggesting that a single 250 ms presentation of a memory item is not sufficient to create stable memory traces. In contrast, subsequent experiments showed that four separate 250 ms presentations of an image are sufficient to yield memory traces roughly half an hour later (Endress & Potter, 2014b). To manipulate the availability of LTM, we thus presented memory items either for durations too fast to yield stable LTM traces (250 ms/picture), or for durations that have yielded relatively stable LTM traces in earlier research (1.5 s/picture).

Materials and method

Design

The experiment had a 2 (PI: unique vs. repeated condition) × 2 (presentation speed: slow vs. fast) × 2 (verbal suppression: present vs. absent) mixed design. The strength of proactive interference (unique vs. repeated) was a within-subject factor; the two PI conditions were administered by blocks, with the order of the blocks counterbalanced across participants. The presentation speed and verbal suppression were between-participant factors.

This design does not separate the contributions of encoding and retrieval operations; rather, our goal was to test whether the availability of verbal resources and of LTM affect memory performance *at all*.

Participants

Fifty-six individuals (14 per condition; 44 females; mean age = 22 years and 12 males; mean age = 29 years) from City University London participated in the experiments below. The sample size was determined by participant availability, subject to the constraint that the effect sizes in Endress and Potter's (2014a) suggest that we should find reliable PI with this sample size. An additional two individuals took part in the experiment, but were excluded from analysis due to computer malfunction (N=1) and excessive breaks and unusual behavior (N=1).

Participants were sequentially assigned to the conditions without verbal suppression and with verbal suppression, respectively. Each participant chose which presentation speed (fast or slow) they wished to take part in, based on the duration of the session they signed up for. The order of the unique and repeated conditions were counterbalanced across participants.

Apparatus

Stimuli were presented on a Dell P2213 22" (55.88 cm) LCD (resolution: 1024 × 640 pixels at 60 Hz), using the Matlab psychophysics toolbox (Brainard, 1997; Pelli, 1997) on a Mac mini computer (Apple Inc, Cupertino, CA). Responses were collected from pre-marked "Yes" and "No" keys on the keyboard.

For the verbal suppression condition, participants were provided with a regular rhythm at which they were to repeat the syllables. We used the Metronomo app (downloaded from the Apple Appstore), set to a tempo of 90 beats per minute and a rhythm of 1 beat per measure (i.e., the sequence of sounds did not comprise any accents). The participants' vocalizations were recorded through a USB webcam (Logitech, Lausanne, Switzerland), using Audacity (Version 2.1.0; http://audacity.sourceforge.net/) and exported to the mp3 format using the LAME MP3 encoder (version 3.98.2, http://lame1.buanzo.com.ar/).

Materials

Stimuli were colour pictures of everyday objects taken from Brady et al. (2008). These were randomly selected for each participant from a set of 2,400. In the unique condition, the stimuli thus came from a randomly selected set of 1,290 pictures; in the repeated condition, a randomly selected set of 22 pictures was used in all trials. There was no overlap between these picture sets.

The pictures were presented at a resolution such that they subtended approximately the same visual angle (approximately 12.7 × 12.7 degrees) as in Endress and Potter (2014a). The syllables participants had to repeat during the verbal suppression task were "vlim," "toff," "plof." These syllables were chosen to have a low phonotactic probability to make it relatively hard to automatize the verbal suppression task.

In the verbal suppression condition, participants were tested individually in a sound attenuated testing room. In the no suppression condition, participants were tested in groups of up to three in a sound-attenuated testing room; participants were separated by screens so that they could not see each other's computer screens. They were seated at a comfortable viewing distance from the computer.

Procedure

Memory task. Participants completed 120 trials in total (60 for each of the unique and repeated conditions); the order of these conditions was counterbalanced across participants.

They were informed that they would view sequences of pictures presented one at a time. After the last picture of the sequence, they would see another picture, and would have to decide whether it has been part of the sequence.

Participants started each trial by a key-press and then viewed instructions to look at the pictures for 1,000 ms, followed by a fixation cross for 300 ms, a blank screen for 200 ms and then a sequence of 21 randomly chosen pictures. Each picture was presented for either 250 ms or 1500 ms, depending on the condition. The sequence of pictures was followed by a question mark ('?') for 800 ms, a blank screen for 900 ms and the test item for 800 ms. Responses were collected from pre-marked keys on the keyboard. The left shift key corresponded to a "new" response, and the right shift key to an "old" response; both keys were marked with post-it notes. Once the response had been recorded the next trial began with a key press.

"New" test items were presented on half of the trials. In the unique condition, completely new images were used. In the repeated condition, the "new" picture was the one image from the set of 22 that was not presented in the sequence. "Old" test items (i.e. those that had been presented in the sequence) were randomly sampled from two initial serial positions (2, 3), two medial serial positions (10, 11), and two final serial positions (19, 20); each position was equally presented in the test items. The very first and last images were never used as test pictures as they were unmasked. A further constraint was that no more than 3 trials could occur in a row that had the same response (yes/no) or the same serial position for the "old" test picture.

Participants in the slow condition were given breaks after the 30^{th}, 60^{th} and 90^{th}

trials whereas those in the fast condition were given a break only after the 60th trial.

Upon completion of the experiment, all participants were given a debriefing questionnaire, where they were asked about the kinds of strategies they had used.

Verbal suppression task. Before completing the main experiment, participants in the verbal suppression condition were pre-familiarized with the nonsense syllables "vlim", "toff" and "ploff." Specifically, the experimenter repeated these syllables for 15 s at a rate of 90 syllables per minute, and asked the participants to repeat these syllables as well. This was repeated until it was clear the task was understood. Participants were instructed to repeat the syllables at a constant rhythm of 90 beats per minute throughout the experiment (i.e. during encoding, maintenance and retrieval).

Participants were told that the verbal suppression task and the memory task had equal importance. The participants' vocalizations were recorded to be checked afterwards to allow for the exclusion of any participants not engaging in verbal suppression.

Analysis

Verbal suppression task. The participants' vocalizations were analyzed in two ways. First, we visually inspected the waveform using the graphical user interface of Audacity (where syllables and their rhythm are clearly visible). We specifically verified whether there were changes in the pronunciation rate as the experiment progressed.

The second analysis consisted of listening to randomly chosen 10 s segments from each recording to verify that participants kept repeating the syllables at the desired rhythm (irrespective of their phase with respect to the metronome tones). We inspected 15 and 5 segments per participants in the slow and the fast conditions, respectively. Specifically, we verified that participants (i) performed verbal suppression throughout the experiment without any long pauses or omissions, (ii) produced the non-sense syllables in the correct order and (iii) pronounced the syllables at the correct rate.

Among the twenty-eight participants, two did not perform the suppression task exactly as intended. One participant tapped the beat of the metronome on four trials whilst performing both verbal suppression and the memory task. As we do not analyze reaction times, exclusion of this participant from the data was not deemed necessary. The other participant increased the rate of repetition on the last 2-3 trials to 270 beats per minute, but performed the suppression task as intended for the rest of the experiment. However, as verbal suppression still took place — as expected for most of the experiment and in a more difficult form for 2-3 trials, this participant's data was retained for analysis as well.

Memory Performance. The results are reported in terms of the percentage of correct responses. The number of correct scores was averaged for each participant.

Analyses in terms of memory capacities as estimated by Cowan's formula (e.g., Cowan, 2001) would yield identical results, because, for a constant sequence length and an equal number of "old" and "new" trials, the memory capacity estimate is linearly related to the proportion of correct responses. However, Endress and Potter's (2014a) results are clearly inconsistent with constant memory capacities in this paradigm; for example, if participants had a capacity of 30 (as estimated for 100 memory items in their experiments), they should be at ceiling for all set sizes below 30, which was not the case (see also Banta Lavenex et al., 2015, for similar results for spatial memory). Hence, we analyze the data in terms of the percentage of correct responses, the hit rate, and the false alarm rate. We will analyze the data using standard ANOVAs as well as using generalized linear mixed models (presented in the Appendix).

We also report signal detection analyses. However, as standard signal detection theory assumes equal variance of the noise distribution and the signal distribution, it would not be appropriate for our data. In fact, there is substantial evidence that the variance of the memory strength of "old" items is larger (by roughly 25%) than of new items, irrespective of whether it is measured directly or from receiver-operant characteristics (e.g., Mickes, Wixted, & Wais, 2007; Ratcliff, Sheu, & Gronlund, 1992, but see Rouder, Pratte, & Morey, 2010). As a result, d' would be an overestimate of the actual discrimination index, and estimates of bias would be biased as well. We thus report non-parametric measures of sensitivity and bias (Macmillan & Creelman, 1996), albeit using the corrected formulae by J. Zhang and Mueller (2005). Specifically, their sensitivity measure A is the average of (a) the minimum area under a (proper) Receiver Operant Characteristic (ROC) curve compatible with the empirically observed hit and false alarm rates, and (b) the maximum area under a (proper) Receiver Operant Characteristic (ROC) curve compatible with the empirically observed hit and false alarm rates, where a “proper” ROC curve lies above the diagonal (i.e., is concave). Their bias measure b is the slope of the ROC curve at the criterion c, and is thus equivalent to the likelihood ratio of the signal distribution and the noise distribution at the criterion c.[1]

Finally, we calculate the cost of PI as the difference of the percentage of correct responses between the unique and the repeated condition, divided by the percentage of correct responses in the unique condition, i.e. $\frac{\text{unique}-\text{repeated}}{\text{unique}}$.

Results

Percentage of correct responses

The results in terms of the percentage of correct responses are shown in Figure 1a. We analyzed the results with an ANOVA with the within-participant predictor PI (Repeated vs. Unique) and the between-participant predictors PI Order (Repeated first vs. unique first), Picture Duration (slow vs. fast), and Suppression (present vs. absent) as well as all interactions. We observed main effects of PI, $\underline{F}(1,48) = 60.65$, $\underline{p} < .0001$, $\eta_p^2 = .519$, suggesting that participants performed better in the unique condition ($\underline{M}$ = 73.96%, $\underline{SD}$ = 11.32%) than in the repeated condition ($\underline{M}$ = 62.38%, $\underline{SD}$ = 10.77%), of Picture Duration, $\underline{F}(1,48) = 46.49$, $\underline{p} < .0001$, $\eta_p^2 = .413$, suggesting that participants performed better for slow presentations ($\underline{M}$ = 74.23%, $\underline{SD}$ = 13.00%) than for fast presentations ($\underline{M}$ = 62.11%, $\underline{SD}$ = 8.28%), and of Suppression, $\underline{F}(1,48) = 7.83$, $\underline{p}$ = .007, $\eta_p^2 = .070$, suggesting that participants performed better without suppression

[1] J. Zhang and Mueller’s (2005) proof is straightforward. If the hit and false alarm rates are parameterized as a function of the criterion c, they are given by $H(c) = \int_c^\infty f_s(x)dx$ and $FA(c) = \int_c^\infty f_n(x)dx$, where f_s and f_n are the signal and noise density functions, respectively. As a result, the derivative of the hit rate as a function of the false alarm rate at the criterion is given by $\frac{dH}{dFA}\big|_{FA=FA(c),H=H(c)} = \frac{H'(c)}{FA'(c)} = \frac{f_s(c)}{f_n(c)}$, which is just the likelihood ratio.

(M = 70.65%, SD = 12.95%) than with suppression (M = 65.68%, SD = 11.49%).

The effect of Suppression was modulated by an interaction between Picture Duration and Suppression, $F(1,48) = 4.39$, $p = .042$, $\eta_p^2 = .039$. We followed up this interaction with separate ANOVAs for the two picture durations, using the same predictors as above except for Picture Duration and all interactions with it. For fast presentations, the effect of Suppression was not significant, $F(1,24) = .42$, $p = .523$, $\eta_p^2 = .017$. When comparing a linear "null" model with only an intercept to a model with an intercept and a slope for Suppression, the likelihood ratio was 4.2 in favor of the null hypothesis after correction for the different numbers of model parameters, using the Bayesian Information Criterion (Glover & Dixon, 2004). In contrast, for slow presentations, the main effect of Suppression reached significance, $F(1,24) = 8.48$, $p = .008$, $\eta_p^2 = .235$, and the likelihood ratio in favor of the non-null hypothesis was 8.0, again after correction with the Bayesian Information Criterion.

The triple interaction between PI, PI Order and Suppression almost reached significance, $F(1,48) = 3.93$, $p = .053$, $\eta_p^2 = .034$.

It should be noted, however, that, when the Holm-Bonferroni correction to the α level is applied, the only effects to reach significance are the main effect of PI ($p_{\text{corrected}} < .0001$ for the overall ANOVA; $p_{\text{corrected}} < .001$ for the follow-up ANOVAs), and of Picture Duration ($p_{\text{corrected}} < .0001$). Hence, at least for fast presentations, participants do not seem to rely on verbal mechanisms when remembering meaningful images (see also Endress & Potter, 2012, for a similar conclusion), even though participants extract conceptual information from images even with fast presentations (e.g., Potter, 1975; Potter, Staub, & O'Connor, 2004). However, we believe that it is useful to know that, for slow presentation rates, we cannot exclude that participants might use verbal strategies. An analysis using a generalized linear mixed model yielded similar results (see Appendix B).

Hits, false alarms, signal detection theory

We next analyzed the results in terms of the hit rates and false alarm rates (see Figure 1b and c). We analyzed the hit rates in an ANOVA with the within-participant factors PI and Serial Position (first vs. middle vs. last), and the between-participant predictors PI Order (repeated first vs. unique first), Picture Duration (slow vs. fast), and Suppression (present vs. absent), as well as all interactions. This ANOVA yielded only a significant main effect of Serial Position, $\underline{F}(2,96) = 36.13$, $\underline{p} < .0001$, $\eta_p^2 = .39$, and a significant triple interaction between PI, PI Order and Serial Position, $\underline{F}(2,96) = 4.78$, $\underline{p} = .011$, $\eta_p^2 = .084$. However, mixed model analyses suggest that this triple interaction is most likely due to two outliers in the middle positions of the repeated condition when participants start with the unique conditions, see Appendix B. (The main effects of Picture Duration, $\underline{F}(1,48) = 3.32$, $\underline{p} = .075$, $\eta_p^2 = .057$, and PI, $\underline{F}(1,48) = 2.95$, $\underline{p} = .092$, $\eta_p^2 = .055$, were only marginal, and should not be considered reliable, given the large number of comparisons we performed.)

In sum, the main results of the analysis of the hit rates is a serial position effect. As shown in Appendix A, this serial position effect reflects an advantage for the last positions, and thus a recency effect.

We analyzed the False Alarm rates in the same ANOVA as the Hit rates; the Serial Position factor was just a pro forma factor, but new items had no serial position of course. This ANOVA yielded a main effect of Picture Duration, $\underline{F}(1,48) = 18.62$, $\underline{p} < .0001$, $\eta_p^2 = .253$, suggesting that False Alarm Rates were higher for faster presentations, ($\underline{M} = 45.65\%$, $\underline{SD} = 25.89\%$) than for slow presentations, ($\underline{M} = 27.26\%$, $\underline{SD} = 26.62\%$), as well as a main effect of PI, $\underline{F}(1,48) = 79.29$, $\underline{p} < .0001$, $\eta_p^2 = .597$, suggesting that false alarm rates were higher in the repeated condition ($\underline{M} = 50.24\%$, $\underline{SD} = 27.12\%$), than in the unique condition, ($\underline{M} = 22.68\%$, $\underline{SD} = 20.78\%$). In other words, both a faster presentation rate and PI boost false alarm rates. Further, it appears that the effects of PI are carried mainly by the false alarm rates, at least in the current experiments (see below for discussion).

Finally, we used signal detection theory to analyze the results. Following J. Zhang and Mueller (2005), we used A as a sensitivity estimate. We analyzed it in an ANOVA with the within-participant predictor PI (Repeated vs. Unique) and the between-participant predictors PI Order (Repeated first vs. unique first), Picture Duration (slow vs. fast), and Suppression (present vs. absent) as well as all interactions (see Figure 2a).

The ANOVA revealed a significant main effect of PI, F(1,48) = 35.19, p < .0001, η_p^2= .394, suggesting that A was higher in the unique condition (M = .80, SD = .11) than in the repeated condition (M = .68, SD = .15). The main effect of Picture Duration was significant, F(1,48) = 28.59, p < .0001, η_p^2= .312, suggesting that A was higher in the slow condition (M = .80, SD = .15) than in the fast condition (M = .69, SD = .11). We also observed a significant main effect of Suppression, F(1,48) = 8.07, p= .007, η_p^2= .088, reflecting that, overall, discrimination was better without suppression (M = .78, SD = .12) than with suppression (M = .71, SD = .15).

We found a marginal interaction between Picture Duration and Suppression, F(1,48) = 3.35, p = .073, η_p^2 = .037. The triple interaction between PI, PI Order and Suppression was marginal as well, F(1,48) = 3.02, p = .089, η_p^2 = .034.

Given the results obtained for the percentage of correct responses above, the marginal interaction between Picture Duration and Suppression was followed up by separate ANOVAs for the fast and the slow condition, respectively. The interactions indicate that the effect of Suppression is only significant for the slow condition, F(1,24) = 8.68, p = .007, η_p^2 = .25, but not in the fast condition, F(1,24) = .69, p = .42, η_p^2 = .027. The effect of PI was significant for both presentation speeds (slow condition: F(1,24) = 17.84, p = .0003, η_p^2 = .389; fast condition: F(1,24) = 18.05, p = .0003, η_p^2 = .423).

However, when applying the Holm-Bonferroni correction to the α level, the only effects to reach significance are the main effect of PI ($p_{\text{corrected}} < .0001$ for the overall ANOVA; $p_{\text{corrected}} < .001$ for the follow-up ANOVAs), of Picture Duration ($p_{\text{corrected}} < .0001$), and of Suppression ($p_{\text{corrected}} = .007$ for the overall ANOVA and the slow condition). As a result, the A analyses thus largely mirror those of the percentage of correct responses: PI, faster presentation rates and articulatory suppression all impair sensitivity, though the effect of suppression was specific to slow presentation rates.

We analyzed b using the same ANOVA as above. A main effect of PI, $\underline{F}(1,48) = 17.86$, $\underline{p} = .0001$, $\eta_p^2 = .258$, suggests that b was higher in the unique condition ($\underline{M} = 1.32$, $\underline{SD} = .63$) than in the repeated condition ($\underline{M} = .87$, $\underline{SD} = .45$). In other words, the criterion for accepting items as "old" was more stringent in the unique condition than in the repeated condition. The main effect for Picture Duration, $\underline{F}(1,48) = 4.40$, $\underline{p} = .041$, $\eta_p^2 = .072$, suggests b was higher in the slow condition ($\underline{M} = 1.20$, $\underline{SD} = .68$) than in the fast condition ($\underline{M} = .99$, $\underline{SD} = .46$). Finally, the main effect of PI Order, $\underline{F}(1,48) = 5.99$, $\underline{p} = 0.018$, $\eta_p^2 = 0.098$, suggests that b was larger when participants started with the repeated condition ($\underline{M} = 1.21$, $\underline{SD} = .68$) compared to when they started with the unique condition ($\underline{M} = .97$, $\underline{SD} = .46$).

The analyses of b largely mirror those of the false alarm rate, except for the main effect of PI order: PI and faster presentation rates (as well as starting with the unique condition) lead to more liberal criteria.

Cost of Proactive Interference

We next analyzed the cost of PI, using performance in the unique condition as a baseline (see Figure 3). Specifically, we computed the difference between performance in the unique and the repeated condition, and divided this difference by the performance in the unique condition.

Visual inspection of Figure 3(a) reveals that the cost of PI is remarkably constant across conditions: Performance in the repeated condition is always about 15% lower than in the unique condition. We first analyzed the cost of PI in an ANOVA with the between-subject factors Picture Duration, PI Order, and Suppression as well as all interactions. Only the interaction between PI Order and Suppression was marginal, $\underline{F}(1,48) = 4.0$, $\underline{p} = .051$, $\eta^2 = .073$. In the no suppression condition, the cost of PI was larger when participants started with the unique condition, $\underline{F}(1,24) = 5.02$, $\underline{p} = .035$,

$\eta^2 = .172$, but there was no difference between the condition orders in the suppression condition, $\underline{F}(1,24) = .64$, $\underline{p} = .431$, $\eta^2 = .025$. However, none of these effects survived when the α level was adjusted using the Holm-Bonferroni method. Mixed model analyses yielded similar results (see Appendix B).

Debriefing questionnaire

To analyze the strategies participants believed to have followed, they were given debriefing questionnaires where they were asked to mention any strategies they might have followed. These questionnaires were analyzed informally by looking for recurring keywords (e.g., “I repeated the words”, “I looked at the color and shape of the picture” and so forth). This analysis revealed 8 distinct strategies, in addition to some participants reporting that they did not use any particular strategy. These strategies were related to (sub-vocal) rehearsal, trying to identify matches between the sample images and the test image in terms of color, size or shape of the objects, categorizing them in terms of particular themes (e.g., furniture, animal, decorative object etc.), creating associations between the different sample pictures, and creating a rhythm with the non-sense syllables so that one of the three suppression syllables carried stress, which apparently made the suppression task subjectively less interfering at least for some participants.

We note that it is not always clear what the participants might have meant, nor do all the answers make sense (e.g., all images had exactly the same size, and the latency of picture naming is just too slow for participants being able to name pictures at 250 ms per picture; e.g., Potter & Faulconer, 1975). Be that as it might, Table 1 presents a tally of the strategies reported by the participants. The main interpretable result was that participants attempted less to rehearse pictures under verbal suppression than without verbal suppression.

Within the fast condition however, the majority of participants either did not use any strategies or simply attended to the general visual appearance of the pictures (i.e. lower level features such as color, shape, size etc.), though we note that research on conceptual short-term memory suggest that participants clearly encode more abstract, conceptual information about the items as well (e.g., Endress & Potter, 2012; Potter, 1975; Potter et al., 2004).

General Discussion

Proactive Interference (PI) is known to limit memory performance over time scales from seconds to years. More controversially, it might also be at the root of the capacity limitations typically observed in (visual) WM. However, even when remembering items over brief periods of time, memory is unlikely to be a unitary phenomenon, and draws on visual, conceptual, linguistic, and attentional processes, among others. In the present research, we start investigating the effects of PI while selectively manipulating some of these contributions. Specifically, we investigated the effects of PI as a function of the availability of verbal processes and of LTM, by manipulating the presence of an articulatory suppression task (that should affect the availability of verbal resources), and by manipulating the presentation speed of the pictures (that should affect the availability of LTM).[2]

We made several important observations. First, and as expected, participants performed better in a situation with less PI, and they performed better when items were presented more slowly. Second, verbal suppression seems to affect performance only for slow presentation rates (though this effect was not significant after Holm-Bonferroni correction), but not for fast presentations, even though participants are perfectly capable of extracting conceptual information at these presentation rates

[2]Interestingly, our presentation speed manipulation might be related to a prominent phenomenon in recognition memory. When studying lists of items, participants often falsely recognize foil items that are related to the study items (e.g., Deese, 1959; Roediger & McDermott, 1995). However, when the study items are paired with pictures of the items (e.g., when the word dog and is shown with a picture of a dog), they are less likely to falsely recognize related foils compared to when the study items are presented only in a verbal format (e.g., when they read a written word and hear a spoken word; Gallo, Weiss, & Schacter, 2004; Gallo, Kensinger, & Schacter, 2006; Gallo, Perlmutter, Moore, & Schacrer, 2008; Israel & Schacter, 1997). This might be because participants expect to retrieve more detailed memory representations when presented with pictures in addition to words, or because pictures provide additional information on top of verbal information (see Potter et al., 2004, for a related conclusion). In our experiments, slower presentation rates might allow for more elaborate verbal encoding, which, in turn, might reduce the participants' propensity to falsely recognize foils. However, if, in our experiments, false alarm rates were reduced by the availability of verbal resources, we would expect an interaction between Suppression and Picture Duration, which we did not observe. At least in our experiments, the reduction in false alarm rates is thus most likely triggered by other processes on top of verbal resources.

(e.g., Potter, 1975; Potter et al., 2004). This supports the view that conceptual and linguistic information can be processed through different channels even very early on in processing (Endress & Potter, 2012).

Third, the cost of PI might have been slightly higher when participants started with unique rather than the repeated condition; if this effect is reliable, it might be because, when participants start with the unique condition, the inherent PI in the repeated condition will be combined with the cumulative PI from the unique condition, which might simply be due to the fact of having seen many pictures before. Alternatively, participants might be more vigilant when starting with the more difficult repeated condition.[3] In line with the latter view, participants adopted a somewhat more conservative criterion when starting with the repeated condition.

Fourth, in the current experiments, the effect of PI seems to be carried more by the false alarm rate than the hit rate, which did not differ across the experimental conditions. However, in Endress and Potter's (2014a), the contributions of the hit rate and the false alarm rate depended on the experiment. As a result, the main effects of PI thus seem to be variable in the current paradigm, perhaps because participants can develop different biases that are optimal in different experiments.

Fifth, and crucially, the cost of PI was relatively constant at about 15% of the performance in the unique condition, across presentation conditions. The cost of PI thus seems to be remarkably insensitive to items variations in the presentation conditions, and seems mainly to depend on the relative memory strength or the relative recency of the target items compared to the interfering items.

These results raise important questions about the mechanisms (if any) that counteract PI. Indeed, these mechanisms are generally believed to be active and effortful (e.g., Braver et al., 2008; Kane & Engle, 2000). However, while WM items are

[3]When the experiments starts with the unique condition, participants can initially endorse pictures if they are vaguely familiar, given that PI is minimized. However, this low criterion would lead to a high proportion of false alarms in the subsequent repeated condition. This possibility predicts that false alarm rates should be lower in both the unique and the repeated condition when participants start with the repeated condition. In other words, when analyzing false alarm rates, we should observe a significant main effect of PI condition order. While false alarm rates were numerically lower when the experiment started with the repeated condition, this effect did not reach significance, though it did reach significance in the analyses of bias.

assumed to be maintained by active and effortful processes as well (e.g., Baddeley & Hitch, 1974; Conway & Engle, 1994; Cowan, 2005; Kane, Poole, Tuholski, & Engle, 2006; Poole & Kane, 2009), the involvement of active and effortful processes is questionable in some experiments, because the presentation rate appears too fast for the deployment of active and effortful processes (e.g., in Endress and Potter's (2014a) and Luck and Vogel's (1997) experiments), and because some WM tasks show only very limited interactions with active attentional tasks (e.g., Fougnie & Marois, 2006; H. Zhang, Xuan, Fu, & Pylyshyn, 2010). The present results do not clarify this issue either. On the one hand, slowing down the presentation should be beneficial for dealing with PI if the mechanisms counteracting PI are active; after all, it is easier to attend to items that are presented more slowly. On the other hand, if PI just happens with few active mechanisms counteracting it, then the cost of PI should be more important when the presentation rate is slowed down; after all, items that are presented more slowly are memorized better, and should thus interfere more as well, and the two effects might well cancel out.[4] As a result, it is an important question to find out whether the remarkable constancy of the cost of PI is a largely inevitable consequence of the relative strength of the target memory items and the interfering items, or if the (active) mechanisms counteracting PI have some fundamental limit beyond which they cannot protect memory from the detrimental effects of PI.

[4]If PI is due to the distinctiveness of the memory trace (e.g., Brown, Neath, & Chater, 2007; Unsworth, Heitz, & Parks, 2008), one would probably predict no effect of presentation rate whatsoever.

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Table 1
Tally of memory strategies reported by the participants. The numbers represent counts, and thus do not sum to the total number of participants.

	No suppression		**Suppression**	
Type of mechanism	**Slow**	**Fast**	**Slow**	**Fast**
Naming/sub-vocal rehearsal	9	4		
Color	4	10	4	7
Size	4	7	4	5
Shape	4	8	4	5
Thematic categorization	4	4	2	
Associations among items	5		3	2
Rhythmic organization of the suppression syllables				2
Responding whether participants *ever* saw a picture				1
No strategies reported		5	2	4

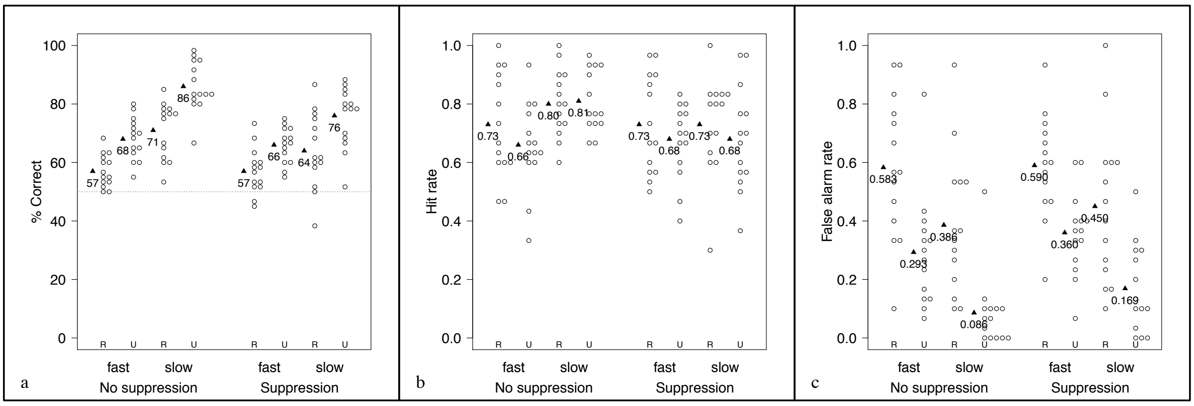

Figure 1. Results in terms of (a) the percentage of correct responses, (b) the hit rate, and (c) the false alarm rate. Circles represent individual participants and the diamond represents the sample average. R stands for the repeated condition, and U for the unique condition.

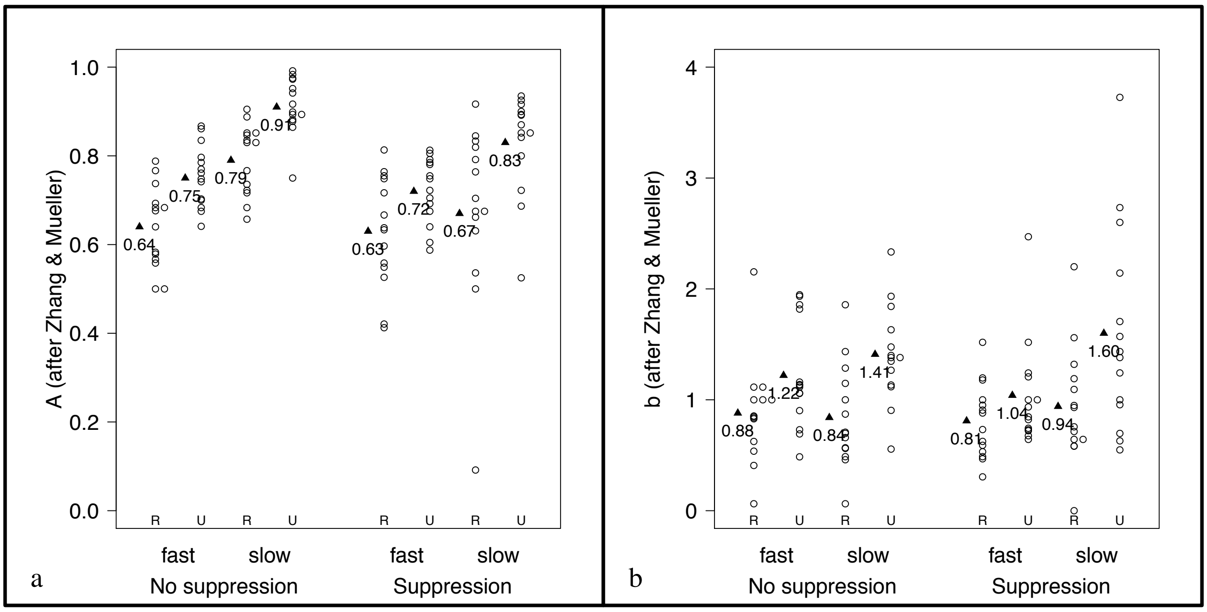

Figure 2. Signal detection theory analyses. (a) Discriminability (*A*) and (b) bias (*b*). Circles represent individual participants and the diamond represents the sample average. R stands for the repeated condition, and U for the unique condition.

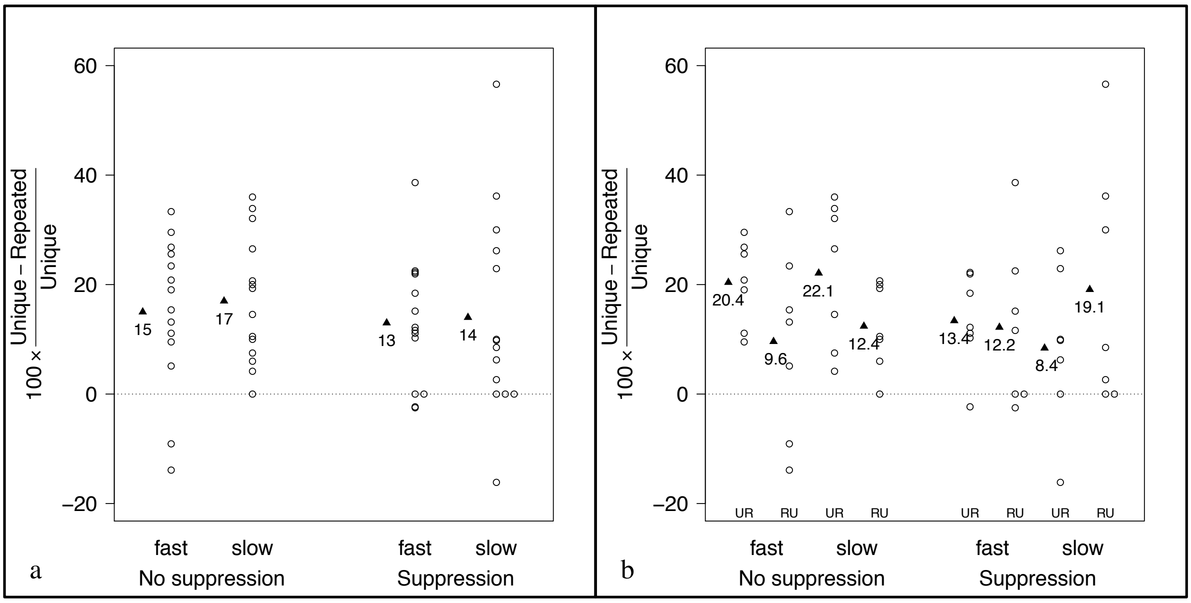

Figure 3. (a) Cost of PI as a function of the factors Presentation Duration and Suppression. (b) Cost of PI as a function of Presentation Duration, Suppression and PI Order. UR stands for unique-repeated, while RU stands for repeated-unique. Circles represent individual participants and the diamond represents the sample average. R stands for the repeated condition, and U for the unique condition.

Appendix A

Serial Position Effects

For "yes" trials, we analyzed the Serial Position effect by collapsing across all other conditions. As shown in Figure B1, there was a recency effect for the last items. While performance did not differ between the initial (M = 67.05%, SD = 16.34%) and the middle positions (M = 68.21%, SD = 16.55%), performance was significantly better for items from the final positions (M = 83.13%, SD = 13.16%) than for items from the initial positions, $t(55) = 6.69$, $p < .0001$, Cohen's $d = .89$, $CI_{.95} = [11.26, 20.89]$, or the middle position, $t(55) = 6.72$, $p < .0001$, Cohen's $d = .9$, $CI_{.95} = [10.46, 19.36]$. (The confidence intervals refer to the confidence intervals for the difference; these differences would also be significant after Holm-Bonferroni correction.)

Appendix B

Analyses with generalized linear mixed models

Percentage of correct responses

We analyzed the data also using a generalized linear mixed-effects model. The initial model comprised the fixed factors PI, PI Order, Picture Duration and Suppression and their interactions as well as a random intercept for participants and random slopes and intercepts for gender, age, and whether or not participants had more than one native language. We then pruned the model to those factors that contributed to the model likelihood (see Baayen, Davidson, & Bates, 2008). The final model comprised only the predictors PI, Picture Duration and Suppression (but not PI Order), and the interaction between Picture Duration and Suppression. We included only a random intercept for participants. Significance was assessed by approximating the t values as Z values.

This model revealed that participants performed better in the unique than in the repeated condition, $\beta = 11.6$, SE = .1.5, $CI_{.95} = [8.6, 14.5]$, $p < .0001$, and that they performed better for slow presentations than for fast presentations, $\beta = 15.8$, SE = 2.6, $CI_{.95} = [10.8, 20.8]$, $p < .0001$. (Confidence intervals refer to the estimates.) The effect of suppression did not reach significance, $p = .624$. However, the interaction between Picture Duration and Suppression revealed that the cost of suppression was greater for slow presentations, $\beta = -7.4$, SE = 3.6, $CI_{.95} = [-14.5, -.4]$, $p = .040$. Follow-up analyses with models using PI and Suppression as fixed factors but no interactions revealed that the effect of Suppression was significant for slow presentations, $\beta = -8.7$, SE = 1.9, $CI_{.95} = [-14.7, -2.7]$, $p = .005$, but not for fast presentations, $\beta = -1.3$, SE = 1.9, $CI_{.95} = [-4.96, 2.46]$, $p = .509$. The effect of PI was highly significant for either presentation duration, $p < .0001$.

Hit and false alarm rate

We analyzed the hit rates using a generalized linear mixed model. The initial model had the random factor Participants and the fixed factors PI, Serial Position (first vs. middle vs. last), PI Order (Repeated first vs. unique first), Picture Duration (slow vs. fast), and Suppression (present vs. absent) as well as all interactions. The final model comprised all the main effects, all 10 double interactions and the triple interaction between PI, PI Order and Serial Position. We observed an enhancement for the last positions relative to the first positions (our baseline level in the factor), β = 14.82, SE = 5.63, $CI_{.95}$ = [3.78, 25.86], p = .009. It also provides an explanation for the triple interaction. Specifically, hit rates for items from middle positions were somewhat lower when participants started with the unique condition, β = -13.93, SE = 6.5, $CI_{.95}$ = [-26.68, -1.18], p = .032. However, this was modulated by the triple interaction above, suggesting that this effect was less pronounced in the unique condition, β = 18.21, SE = 9.20, $CI_{.95}$ = [.19, 36.24], p = .048. Figure B1(b) reveals that this is most likely due to two outliers in the middle positions of the repeated condition when participants start with the unique conditions. (Outliers are defined as differing by more than 1.5 interquartile ranges from the lower quartile.) Visual inspection of the box and whiskers plot in Figure B1(b) shows that the serial position effects were relatively similar across conditions. As a result, we will ignore these double and triple interactions.

We analyzed the false alarm rates using a generalized linear mixed model. The initial model had the random factor Participants and the fixed factors PI, PI Order (Repeated first vs. unique first), Picture Duration (slow vs. fast), and Suppression (present vs. absent) as well as all interactions. The final model comprised the main effects and all 6 double interactions. The model revealed that the false alarm rate was significantly lower for slow presentations, β = -20.60, SE = 8.02, $CI_{.95}$ = [-36.32, -4.87], p = .010, and significantly lower in the unique condition, β = -26.43, SE = 6.23, $CI_{.95}$ = [-38.64, -14.22], p $<$ .0001.

Cost of Proactive Interference

We analyzed the cost of PI in a general linear model with the fixed factors Picture Duration, Suppression and PI Order as well as all interactions and random intercepts for age and multilingualism. We then removed predictors from the model that did not contribute to the model likelihood.

The final model comprised simple predictors for Picture Duration, Suppression and PI Order, the interaction between Suppression and PI Order, as well as a random intercept for multilingualism. (All estimates below reflect the cost of PI in percentage of the performance in the unique condition.) This model revealed that the cost of PI was slightly higher when starting with the unique condition β = 20.2, SE = 5.2, $CI_{.95}$ = [.04, 20.4], p = .049. This effect was modulated by an interaction between Suppression and PI Order, whose magnitude revealed that almost the entire effect of PI Order was due to the no suppression condition, β = -15.0, SE = 7.4, $CI_{.95}$ = [-29.4, -.6], p = .042. Accordingly, the effect of PI Order was only significant in the no suppression condition, β = 10.2, SE = 4.5, $CI_{.95}$ = [1.5, 19.0], p = .022, but not in the suppression condition, β = -4.5, SE = 5.9, $CI_{.95}$ = [-16.4, 6.9], p = .423.

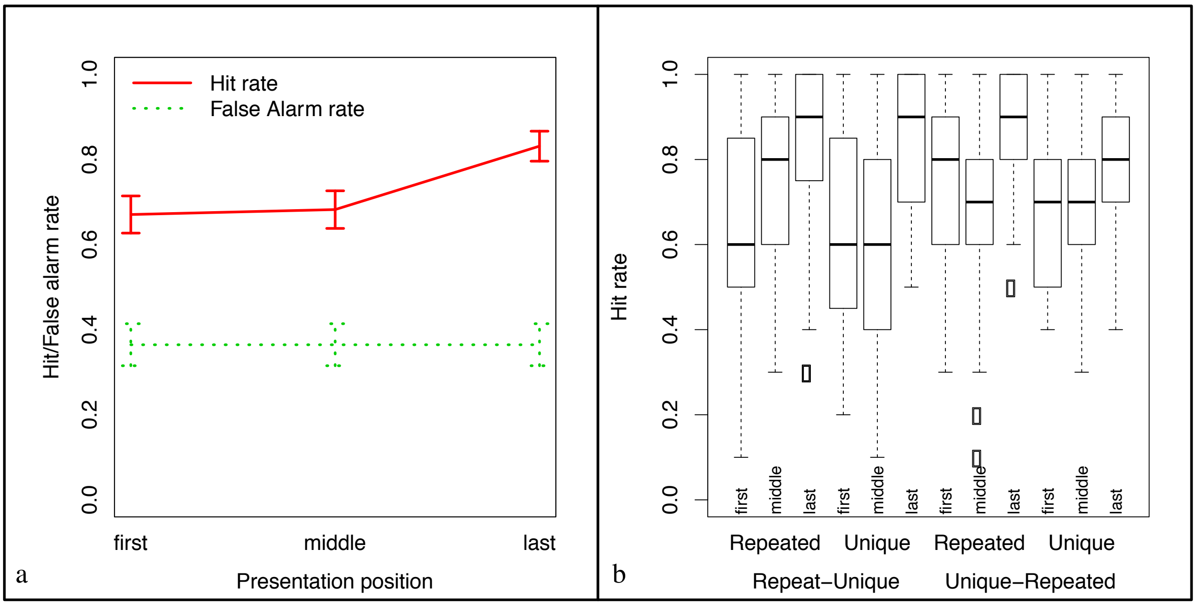

Figure B1. (a) Serial position effects collapsed across all conditions. Error bars represent standard errors from the mean. (b). Serial position effects as a function of the PI Order and the PI. Boxes extend from the lower to the higher quartile. The thick line represents the median, and the whiskers the range of the data points within 1.5 interquartile ranges from the lower and the higher quartile, respectively. The circles represent outliers outside of this range.