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Effects of Proactive Interference on Non-Verbal Working Memory

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Abstract

Working memory (WM) is a cognitive system responsible for actively maintaining and processing relevant information and is central to successful cognition. A process critical to WM is the resolution of proactive interference (PI), which involves suppressing memory intrusions from prior memories that are no longer relevant. Most studies that have examined resistance to PI in a process-pure fashion used verbal material. By contrast, studies using non-verbal material are scarce, and it remains unclear whether the effect of PI is domain-general or whether it applies solely to the verbal domain. The aim of the present study was to examine the effect of PI in visual working memory using both objects with high and low nameability. Using a Directed-Forgetting paradigm, we varied discriminability between WM items on two dimensions, one verbal (high-nameability vs. low-nameability objects) and one perceptual (colored vs. gray objects). As in previous studies using verbal material, effects of PI were found with object stimuli, even after controlling for verbal labels being used (i.e., Low-Nameability condition). We also found that the addition of distinctive features (color, verbal label) increased performance in rejecting intrusion probes, most likely through an increase in discriminability between content-context bindings in WM.

Keywords

Interference/inhibition in memory retrieval; Working memory; Directed forgetting; Object recognition; Recollection

Introduction

Working memory (WM) is a cognitive system responsible for actively maintaining and processing relevant information and is central to successful cognition. (Baddeley 1986) proposed a model of WM consisting of two subsystems for storing verbal and visuospatial

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content, as well as central executive processes that regulate the information in the storage subsystems. Of these executive processes, putative inhibitory (also sometimes called interference-control) processes are involved in protecting the contents of WM from interference from competing external stimuli or internal representations, such as prior memories (Baddeley 1990; Keppel and Underwood 1962). Interference from prior memories, whether these are stored in long-term or short-term (working) memory, is referred to as proactive interference (PI). For instance, the memory trace of a previously encoded word or an image may affect the ability to recollect another word or image. The effects of PI in WM and the cognitive processes involved in its resolution have been studied extensively in the verbal domain; however, less is known about the effects of PI in visual WM (see Jonides and Nee 2006 for a review). The goal of the present study is therefore to provide a clearer understanding of the effects of PI in visual WM using objects as content.

The ability to resolve PI appears to be critical to higher cognitive functions: It is thought to contribute to short-term forgetting (Brown 1958; Keppel and Underwood 1962; Peterson and Peterson 1959) and is positively associated with WM capacity (Bunting 2006; Chiappe et al. 2000; Conway and Engle 1994; May et al. 1999; Rosen and Engle 1998; Whitney et al. 2001), which in turn is positively associated with many ongoing higher cognitive functions, including general intelligence, learning, reasoning, language-processing, and problem-solving (Baddeley 1996; Daneman and Carpenter 1980; Daneman and Merikle 1996; Fry and Hale 2000; Just and Carpenter 1992; Kane and Engle 2002). Furthermore, variations in the ability to resolve PI has been considered a basic mechanism of cognitive development (Diamond and Gilbert 1989; Ridderinkhof et al. 1997) as well as a significant source of decline in cognitive skills with normal aging (Hasher and Zacks 1988; McDowd et al. 1995). Finally, impairments in this ability have been associated with various disorders including schizophrenia (MacQueen et al. 2003; Nestor and O’Donnell 1998) obsessive-compulsive disorder (Enright and Beech 1993) and depression (Joormann 2005; Joormann et al. 2010).

In contemporary models of WM, active maintenance of representations involves binding content information to its context, and according to such models, PI can be defined as the competition between content-context bindings (Nee and Jonides 2013; Oberauer 2002; Oberauer 2009). In an experimental task, context refers to information that may be associated with the maintained items (i.e., the content), such as the color or the location or the current trial. For example, a participant may be asked to decide whether a probe item presented in a given location was initially presented in that particular location. If the probe item had initially been presented in a different location, the current item-location binding would compete with the previously encoded bindings required for accurate decision (i.e. the binding between the current item and its initial location, or the between the current location and the item initially presented there). Compatible with this conceptualization of WM and of competing content-context bindings, PI is thought to be greater when items share similarities along dimensions relevant to target selection (Atkins et al. 2011; Craig et al. 2013). Based on this view, the various features of the items in WM may facilitate recollection if they are distinctive and improve discriminability between bindings, or, conversely, induce forgetting if they overlap and diminish discriminability between bindings (Lewandowsky et al. 2009; Oberauer and Kliegl 2006). In the present study, we were thus specifically interested in examining whether variations in the number of feature codes available for encoding would facilitate recollection (of content-context bindings) in the face of PI.

A large body of research has examined the effects and resolution of PI in verbal WM (Bissett et al. 2009; Bunge et al. 2001; Eich et al. 2014; Jonides et al. 1998; Nee and Jonides 2008; Nee et al. 2007; Nelson et al. 2003; Smith et al. 2011; Yi and Friedman 2014; Zhang et al. 2003). By contrast, studies using non-verbal material are scarce, and it remains unclear whether the effects of PI are domain-general or whether they differ across the visual and verbal domains. Among the few studies that have examined the effects of PI in non-verbal WM, the findings are mixed. Several studies on visual WM that controlled for participants' use of verbal strategies have found a robust effect of PI, similar to that reported for verbal WM (Endress and Potter 2014; Hartshorne 2008; Shipstead and Engle 2013). Other studies using a Recent-Probe task with both verbal and non-verbal material have shown evidence of an equal or stronger PI effect (relative to verbal material) with faces (Brandon et al. 2003; Postle et al. 2004), non-nameable patterns (Badre and Wagner 2005) and locations, but not with color or simple shapes (Postle et al. 2004). Furthermore, Mecklinger et al. (2003) showed a greater effect of PI with verbal material (letters) in individuals with low span capacity and conversely, a greater effect of PI with visual non-verbal material (non-nameable objects) in individuals with a high span capacity.

The mixed findings of PI effects with non-verbal visual material may have to do with the fact that stimuli in visual WM tasks using non-verbal material are more varied than in verbal WM tasks or that the representations of these stimuli are more distributed, thereby eliciting variable levels of PI and requiring more diverse and less consistent control processes to resolve it (Courtney 2004). Additionally, given that visual WM capacity is highly limited (Luck and Vogel 1997) and that visual memory is rapidly dissipated upon presentation of new visual inputs (Landman et al. 2003; Makovsik and Jiang 2007), it is possible that the abstract objects used in Mecklinger et al.'s (2003) study and simple object features such as the color and shape stimuli used by (Postle et al. 2004) may have left impoverished representations (i.e. fewer features encoded) which were easier to release from memory (especially in individuals with low span capacity; Mecklinger et al. 2003), thereby lowering the demands on PI resolution. All in all, the paucity of non-verbal studies examining PI resolution, combined with the great variability of stimuli used in visual WM tasks with non-verbal material, have led to inconsistent results which make it difficult to draw conclusions about the effects of PI in non-verbal visual WM.

In the present study, we examined the effects of PI in visual WM using objects. Recognizing that many visual objects are themselves readily nameable, we included both objects with high (HN) and low (LN) levels of nameability. To assess how easily named the various objects were, we conducted a first experiment in which for each object, participants were asked both to provide a label and to judge how difficult it was to name the object. Furthermore, in this first experiment, another group of participants was asked to judge how visually complex each object was, regardless of how familiar or unfamiliar the object was. This was done to ensure that the visual complexity of the images used as stimuli did not differ between the nameable and non-nameable objects, and to assess any potential confounding effect of image complexity in participants' performance during the WM task.

In a second experiment, using a variant of the short-term item-recognition tasks (Sternberg 1966), we varied discriminability between WM items on two dimensions, one verbal (nameable vs. non-nameable objects) and one perceptual (colored vs. gray objects). We hypothesized that object stimuli would yield similar effects of PI on behavioral performance as those consistently observed with verbal material. We further hypothesized that the addition of features (color, verbal label) available for binding to the task-relevant context (location) would increase discriminability between items in WM and facilitate recollection and the resolution of PI. We did not expect, however, to find an effect of image complexity on participant's performance during the WM task, given previous report that similarity between the probe and the memory items, but not object complexity, is associated with reduced visual WM capacity (Awh et al. 2007).

Experiment 1

Methods

Participants—Participants were sixty adults (40 females; ages 18–29), equally divided into two groups. Participants were college students recruited through flyers, introductory classes and word of mouth, and were compensated $10/hr. Informed consent from all participants was obtained in accordance with the University of Michigan Institution Review Board.

Materials and Procedure—Colored images of 100 nameable and 100 non-nameable objects were sequentially displayed on a monitor screen. The nameable objects were obtained through the Computational Perception and Cognition laboratory (Konkle et al. 2010) and the Bank of Standardized Stimuli (BOSS; Brodeur et al. 2010) and the non-nameable objects were obtained through the Novel Object and Unusual Name (NOUN) Database (Horst and Hout 2015) and the Museum of Modern Art (MoMA) website. Images of all the stimuli are presented in the Appendix. In the first group, using a computer keyboard, participants were asked to type in a name for each object and to grade on a scale of 1 to 7 how difficult it was to name the object, 1 being very easy and 7 being very difficult. In the second group, participants were asked to grade on a scale of 1 to 7 how visually complex each object was, 1 being very simple and 7 being very complex. Participants were told to rate complexity based on visual information alone, regardless of how familiar or unfamiliar the object was. Participants were given unlimited time to input each answer. The images were presented in a randomized order.

Two measures of object nameability were calculated for each object. The first measure, Name Count, consisted of the proportion of different names (i.e. the proportion of unique names) provided for a given object across all participants. That is, the total number of unique names divided by the total number of names given. The second measure, Difficulty Score, was the naming-difficulty score attributed to each object, averaged across participants.

Two measures of object complexity were also defined for each object. The first, named Subjective Complexity, was a subjective measure defined as the complexity score attributed to each object, averaged across participants. The second, named Objective Complexity, was an objective measure of image complexity based on data compression. Compression-based image complexity is a standard measure that comes from information theory and aims to approximate the length of the shortest binary computer program that describes an object (i.e. Kolmogorov complexity; Cover and Thomas, 2006). JPEG compression size reflects the complexity of an image based on multiple visual dimensions (Donderi 2006a; Donderi 2006b) and was found to correlate (average $r = .70$; range = .59-.82) with subjective complexity measures based on human perception (Chikhman et al. 2012; Donderi 2006b; Forsythe et al. 2008; Palumbo et al. 2014). We therefore used the file size (in bytes) of each image after JPEG compression as our objective measure of image complexity. We considered that all images having identical dimensions and all objects being approximately of equivalent size, greater compressed file size would be associated with more complex images whereas smaller compressed file size would be associated with less complex images (Cilibrasi and Vitanyi 2005).

Results and Discussion

We conducted two independent t-tests, using each nameability measure as a dependent variable and stimulus type (HN and LN) as the independent variable, in order to test that objects in the non-nameable condition were indeed significantly judged as less nameable than the objects in the nameable condition. Both measures yielded a robust difference between the two stimulus types (Name Count: $t(198) = 23.866$, $p < .001$; Difficulty Score: $t(198) = 38.124$, $p < .001$), with HN objects having a smaller proportion of different names attributed to them ($M = 0.23$, $SD = 0.16$) and a lower naming difficulty ($M = 1.87$, $SD = 0.48$) than LN objects (Name Count: $M = 0.74$, $SD = 0.15$; Difficulty Score: $M = 4.88$, $SD = 0.62$). In short, both measures of nameability yielded robust differences between HN and LN objects. Thus, we conclude that our choice of what we called “high-nameability” and “low-nameability” objects in fact largely corresponded to those two labels.

We also conducted two independent t-tests between the two stimulus types (HN and LN), using each measure of image complexity as a dependent variable. We found no significant difference in complexity for either measure (Subjective Complexity: $t(198) = 313$, $p = .755$; Objective Complexity: $t(198) = 1.281$, $p = .202$) between HN (Subjective Complexity: $M = 3.52$, $SD = 0.97$; Objective Complexity: $M = 185.76$ Kb, $SD = 158.60$ Kb) and LN (Subjective Complexity: $M = 3.49$, $SD = 0.88$; Objective Complexity: $M = 210.52$ Kb, $SD = 110.40$ Kb) objects. We therefore conclude that both stimulus types are comparable in terms of visual complexity and only differ in terms of nameability.

Experiment 2

In Experiment 1, we demonstrated the validity of our classification of objects as nameable and non-nameable, allowing us to confidently use these objects as stimuli in a short-term item recognition task with the aim of examining the influence of item nameability on the effect of PI in visual WM. In addition to nameability, we also varied perceptual features (colored versus grayscale) of the stimuli in order to assess the effect of item discriminability on the resolution of PI.

Methods

Participants—Forty-eight adults (33 females; ages 18–27) participated in the study. Participants were college students recruited through flyers, introductory classes and word of mouth, and were compensated $10/hr plus a bonus for fast and accurate performance. Informed consent from all participants was obtained in accordance with the University of Michigan Institution Review Board.

Materials and Procedure—The Directed-Forgetting task (also known as the Suppress task, Muther 1965) was used to assess participants' WM performance under PI. In this task, participants were presented with a small set of items (e.g., words or objects) and were instructed to commit the items to memory. After a retention interval, participants were cued to remember only a subset of the memory items. After a second delay, participants were then shown a recognition probe and had to respond whether the probe was a member of the set or not. PI was measured as the difference in performance between two types of probes requiring a negative response: Lure (i.e., items that matched a member of the to-be-forgotten subset of the current trial) and Control (i.e., novel items that were not committed to memory) probes.

To examine the effect of object nameability and color on PI in visual WM, we used a 2 x 2 mixed design, with Color (Color vs. Gray) as a between-subjects variable and Nameability (HN vs. LN) as a within-subjects variable. As such, half of the participants ($n = 24$) were presented with colored images of objects (i.e. those used in Experiment 1), and half ($n = 24$) were presented with grayscale images of the same objects. Using Color as a between-subjects variable ensured minimized contamination that may result from viewing both grayscale and colored versions of the same objects. Participants in each group completed two experimental conditions, one with nameable objects, and one with non-nameable objects. The order of nameable and non-nameable conditions was counterbalanced across participants.

As depicted in Figure 1, each trial began with 1s of fixation, followed by a memory set of 4 centrally displayed objects presented for 4s and retained in memory during a retention interval of 2s. This interval was followed by a cue (arrow pointing up or down) that indicated to subjects to remember the two objects of the top row vs. the two objects of the bottom row or vice versa. After a 2s delay, a probe object was presented. The subject was instructed to respond affirmatively (by pressing a key with the left index finger) if the probe matched either of the to-be-remembered objects or negatively (by pressing a key with the right index finger) if it did not.

On 50% of the trials, the probe was a member of the target set that should still be in WM (Valid probes); on 25% of the trials, the probe matched one of the objects presented in the initial memory set but that had not been indicated as relevant and hence required a negative response (Lure probes), and on the remaining 25% of the trials the probe was an object that had not been presented on that trial (Control probes). Control probes were restricted to stimuli that had not appeared for at least 3 subsequent trials to minimize the effects of PI.

The Nameable and Non-nameable conditions were tested in two different sessions. Each session consisted of 8 blocks of 24 trials, including 12 Valid trials, 6 Control trials, and 6 Lure trials. The objects were randomly drawn from a pool of 100 nameable objects and 100 non-nameable objects. Before beginning the experiment, subjects were given written and oral instructions, and completed 24 practice trials under supervision by an experimenter using stimuli from different pools of HN and LN objects than those used during the experimental trials. Accuracy and reaction time (RT) feedback were provided after each practice trial, and average accuracy and RT were presented after each block of experimental trials.

Statistical Analyses—RT's were calculated for correct trials only. For each probe type, trials on which RT exceeded 2.5 standard deviations from each participant's individual mean were considered as outliers and were removed from the data set (2.9% of the responses were discarded for that reason). Repeated measures analyses of variance (ANOVAs) were performed separately on error rate (ER) and RT data, using a 2 x 3 x 2 mixed design with Nameability (HN, LN) and Probe Type (Valid, Control, Lure) as within-subject factors, and Color (Color, Gray) as a between-subject factor.

To explore further the relationship between the level of nameability of objects and the effect of PI on performance during short-term item recognition, multilevel regression analyses were carried out using maximum-likelihood estimation. Participants' performance in Experiment 2 for which the effect of PI was found to be moderated by Nameability (as revealed by the repeated measures ANOVAs) was therefore modeled as a function of variations in object Nameability (using nameability scores obtained in Experiment 1), Probe Type, and the interaction between Probe Type and Nameability. Similarly, participants' performance was also modeled as a function of variations in object complexity (using Complexity scores obtained in Experiment 1), Probe Type, and the interaction between Probe Type and Complexity. Given the fact that we did not expect to find any effect of image complexity on participants' performance and that measures of complexity were included as control variables, we aimed to maximize our power to detect such effects. Therefore, we tested four separate regression models, in which either measure (i.e. Name Count, Difficulty Score, Subjective Complexity and Objective Complexity) moderated the effect of performance in Experiment 2.

This statistical procedure permitted the analysis of unbalanced data (unequal numbers of data points among participants because of varying numbers of trials and trial types associated with each probe object) and the simultaneous investigation of between-subject and within-subject effects. A random effect for intercept and fixed effects for our predictors and moderators of interest were included. A first-order auto-regressive covariance structure was used, which can accommodate the expected correlations between unexplained variance from one time point to the next. Specifically, given our hypothesis that distinctive features such as verbal labels mitigate PI by increasing bindings between memorized items and the context in which they were presented, we were interested in examining whether object nameability had a greater effect on participants' performance in the Lure trials relative to the Control trials. Additionally, given that similar mechanisms are likely involved when endorsing an item as part of the target set, we expected that object nameability would also have a greater effect on participants' performance in the Valid trials. Finally, given our hypotheses, we did not expect any effect of object Complexity on performance.

Results

Descriptive statistics for each Probe Type and pairwise comparisons between Probe Types are presented in Tables 1 and 2 for ER and RT, respectively. For ER, we found a general effect of PI across all experimental conditions, and this effect was moderated by both object nameability and color. Specifically, main effects of Probe Type ($F(2,92) = 20.947$, $p < .001$, $\eta_p^2 = .313$), Nameability ($F(1,46) = 30.163$, $p < .001$, $\eta_p^2 = .396$) and Color ($F(1,46) = 7.204$, $p = .010$, $\eta_p^2 = .135$) were found, as well as significant Probe Type x Nameability ($F(2,92) = 7.960$, $p = .001$, $\eta_p^2 = .148$) and Probe Type x Color ($F(1,46) = 3.479$, $p = .035$, $\eta_p^2 = .070$) interactions. No Color x Nameability ($F(1,46) = 2.768$, $p = .103$, $\eta_p^2 = .057$) nor Probe Type x Color x Nameability ($F(2,92) = 0.581$, $p = .561$, $\eta_p^2 = .012$) interaction was found. Follow-up pairwise comparisons revealed that for all experimental conditions, ER in the Control trials were significantly lower than in both the Valid and Lure trials ($p < .005$). The Valid and Lure trials did not significantly differ from each other in terms of ER. Importantly, the datum of major interest was the difference between the two kinds of negatives (Lure vs. Control) as the hypothesized main index of PI resolution. Follow-up analyses on the Lure-Control difference scores revealed that the Lure-Control effect on ER was greater with LN ($F(1,46) = 15.950$, $p <.001$, $\eta_p^2 = .257$) and Gray objects ($F(1,46) = 6.097$, $p = .017$, $\eta_p^2 = .117$). The effects of Lure-Control on ER for each condition are presented in Figure 2.

For RT, we also found a general effect of PI across all conditions, but in contrast with ER data, this effect was not moderated by object Nameability or Color. Specifically, main effects of Probe Type ($F(2,92) = 44.059$, $p < .001$, $\eta_p^2 = .489$) and Nameability ($F(1,46) = 12.957$, $p = .001$, $\eta_p^2 = .220$) were found. No main effect of Color ($F(1,46) = 1.151$, $p = .289$, $\eta_p^2 = .024$) and no Probe Type x Nameability ($F(2,92) = 0.754$, $p = .473$, $\eta_p^2 = .016$), Probe Type x Color ($F(2,92) = 0.083$, $p = .920$, $\eta_p^2 = .002$) Nameability x Color ($F(1,46) = 1.646$, $p = .206$, $\eta_p^2 = .035$) nor Probe Type x Nameability x Color ($F(2,92) = 0.113$, $p = .893$, $\eta_p^2 = .002$) interaction was found. Follow-up pairwise comparisons revealed that for all experimental conditions, RT on the Lure trials was significantly greater than on the Valid and Controls trials ($p < .05$). No difference in RT was found between the Valid and Control trials. Although the overall RT across all probe types was greater with Non-nameable objects, the Lure-Control effect did not differ between the HN and LN conditions. The effects of Lure-Control on RT for each condition are presented in Figure 3.

Multilevel regression analyses on participant's ER, modeled as a function of Probe Type, variations in object Nameability, and the interaction between these two factors revealed that both nameability measures significantly predicted ER performance on all probe types, such that lower nameability predicts poorer performance. The main effects of Nameability on ER for each probe type and pairwise comparisons of these effects between Probe types are presented in Table 3. The effects of Nameability on ER for each Probe Type are presented in Figure 4. A significant interaction between Nameability and Trial Type (Name Count: $F(2,6507) = 4.33$, $p < .05$; Difficulty Score: $F(2,6507) = 4.78$, $p < .001$) was also found.

Crucially, for both nameability measures, we found that Nameability was a stronger predictor of participant's ER on the Lure trials than on the Control trials ($p < .05$). Finally, we found a similar effect of Nameability on ER in Valid relative to Control trials ($p < .005$). Similar analyses revealed that object Complexity did not significantly predict ER performance on any Probe Type, as no main effect of Complexity (Subjective Complexity: $F(1,6507) = 1.12$, $p = .290$; Objective Complexity: $F(1,6507) = 0.04$, $p = .833$) nor Complexity x Probe Type interaction (Subjective Complexity: $F(2,6507) = 1.07$, $p = .344$; Objective Complexity: $F(2,6507) = 0.06$, $p = .939$) was found.

Discussion

In this experiment, we showed significant differences between Lure and Control trials for both ER and RT performance in all experimental conditions, indicating a robust effect of PI in visual non-verbal WM. These results are compatible with the effects reported in studies of verbal WM (Bissett et al. 2009; Bunge et al. 2001; Eich et al. 2014; Jonides et al. 1998; Nee and Jonides 2008; Nee et al. 2007; Nelson et al. 2003; Smith et al. 2011; Yi and Friedman 2014; Zhang et al. 2003). Moreover, we found that nameability and color moderate these effects on ER performance, such that more accurate performance was observed with HN and colored objects than with LN and gray objects. This finding suggests that PI may be more successfully overcome when, for each item, multiple features (i.e., verbal label and color) are encoded in association with the task-relevant context (i.e., location), which in turn increases discriminability between items in the memory set and facilitates recollection of contextual bindings (Oberauer 2002).

The regression analyses further confirmed the association between object nameability and the ability to correctly recognize each object as belonging to the target set (Valid) as well as to correctly suppress its memory when no-longer relevant (Lure). Indeed, both measures of nameability used in Experiment 1 revealed that lower levels of verbalization of the object probe predict decreased accuracy in correctly accepting Valid probes and rejecting Lure and Control probes in Experiment 2. Furthermore, the regression analyses did not show any effect of image complexity on ER performance, ruling out the hypothesis that differences in visual complexity across the stimuli might confound our results regarding the effect of nameability.

However, unlike ER performance, we did not observe a moderation of the PI effect on RT by object nameability or color. A possible explanation is that participants used a different strategy in the more difficult conditions (i.e. non-nameable and gray) leading to different speed-accuracy tradeoff across conditions.

General Discussion

In this study, we examined PI-related performance on a directed-forgetting task with nameable, non-nameable, grayscale and colored objects as stimuli. In Experiment 2, we showed an effect of PI on ER and RT in all stimulus conditions, replicating previous findings for verbal WM (Bissett et al. 2009; Bunge et al. 2001; Eich et al. 2014; Jonides et al. 1998; Nee and Jonides 2008; Nee et al. 2007; Nelson et al. 2003; Smith et al. 2011; Yi and Friedman 2014; Zhang et al. 2003), suggesting that non-verbal and verbal contents engage similar mechanism of PI-resolution in short-term recognition. These results are consistent with the view that the effect of PI is domain-general rather than specific to verbal content.

Regarding the role of verbalization in PI resolution, this study revealed that the level of nameability of the stimuli moderates and linearly predicts the effect of PI on ER, such that higher nameability was associated to more accurate performance. Verbal labelling thus appears to play a facilitating role in resolving PI caused by irrelevant information in WM. Beyond verbal coding, Experiment 2 also showed that the effect of PI was greater for gray objects in comparison to colored objects, suggesting that the addition of color information that leads to more discriminability between objects also facilitates the resolution of PI. In contrast to the Nameability and Color variables, no relationship was found between object complexity and the PI-effect on participants' performance.

These results support the idea that PI occurs when items share similarities along dimensions relevant to target selection (Atkins et al. 2011; Craig et al. 2013). This view is compatible with models of WM describing PI in terms of competition between content-context bindings or lack of discriminability among them (Nee and Jonides 2013; Oberauer 2002; Oberauer 2009). In the present study, the addition of task-relevant semantic (verbal label) or perceptual (color) information increased the number of possible features to be bound to a given context (i.e., location), which in turn improved discriminability between items and competing bindings, thereby facilitating the recollection of the bindings relevant for accurate decision. This view is supported by our findings that color and nameability in Experiment 2 are associated with more accurate performance on both Lure and Valid trials. The reduced Lure-Control ER when additional task-relevant item features are present is also compatible with the idea that PI is resolved through recollection of content-context bindings. Finally, our results are consistent with previous findings showing that similarity between the probe and the memory items, but not object complexity, is associated with reduced visual WM capacity (Awh et al. 2007).

It remains unclear, however, whether the presence of verbal labels helps to resolve PI simply through increased discriminability or through another mechanism specific to verbal processing. Moreover, it is possible that the effect of adding color to the objects stimuli on PI-resolution might itself relate to nameability if the colored objects are more nameable than the grayscale objects. Future studies examining the effects of systematic variations in perceptual versus verbal features on PI could shed light on this question.

An alternate, but not incompatible, account of our results may be that participants' performance is influenced by whether or not they remember the source (i.e., context) of a familiar item (i.e., Valid and Lure probes). In the Suppress task, both Valid and Lure probes are familiar relative to Control probes and decision based on familiarity signal would lead to their greater acceptance (correct in the case of Valid probes, and incorrect in the case of Lure ones). Hence, in the absence of source information, familiarity signals could lead to difficulty in rejecting Lures. In this conceptual framework, the addition of feature codes may strengthen the bindings between and item and its source, thereby facilitating the accurate rejection of familiar but to-be-forgotten Lure probes.

The results of the current study have implications that extend beyond understanding the effects of PI and its resolution in normal cognition. The inability to mitigate irrelevant information in WM, resulting in the inability to suppress intrusive thoughts, has been linked to a number of psychological disorders including schizophrenia (Eich et al. 2014; MacQueen et al. 2003; Nestor and O'Donnell 1998; Smith et al. 2011). In these studies, behavioral and neural deficits associated with PI resolution were obtained using verbal material. It is not clear, however, whether these deficits generalize to non-verbal material. Furthermore, the experimental paradigm used in the present study (i.e. the Directed-Forgetting or Suppress task) was recommended by the Cognitive Neuroscience Treatment Research to Improve Cognition in Schizophrenia (CNTRICS) as a promising imaging biomarker measure of interference control (Barch et al. 2012). Crucially, the present non-verbal form of the task would be particularly useful for translation across human and animal research.

A recent study used the Recent-Probes task with objects and found that patients with schizophrenia were less susceptible to PI than healthy (Kaller et al., 2014). These results contrast with findings previously reported by Smith et al. (2011) and Eich et al. (2014). One possible explanation of this discrepancy, provided by Kaller et al. (2014), has to do with differences in the task design in those studies. Specifically, in the Recent-Probes task, familiarity-induced interference comes from previously relevant information encoded in the preceding trial (trial n-1). In contrast, in the Directed-Forgetting task, a subset of an overall set of concurrently encoded items has to be unselected upon presentation of a cue. The authors hypothesized that, relative to the Recent-Probes task, the resolution of PI in the Directed-Forgetting task places more demands on WM selection than on updating processes. An alternative explanation of the different findings is that impaired cognitive control over maintained information in schizophrenia is specific to verbal WM. If having more feature codes is critical to the resolution of PI, then the prediction would be that in Kaller et al's (2014) study, patients with schizophrenia retrieve more feature codes with nameable objects than do healthy controls, in turn suggesting that patients have a fundamentally richer representation of the objects that mitigate PI. Consistent with this view, there is evidence of enhanced mental imagery ability in schizophrenia (Bocker et al. 2000; Matthews et al. 2014; Mintz and Alpert 1972; Sack et al. 2005) and that visual WM and visual imagery both rely on depictive representations that share the same format (Borst et al. 2012). Using the present task with non-nameable objects to examine the resolution of PI in non-verbal visual WM in schizophrenia would allow us to tease apart these two alternate hypotheses.

In summary, the present study offers a unique contribution to the literature by showing that the addition of non-overlapping features such as color and verbal label facilitates the resolution of PI. The present work also provided a plausible explanation as to why previous studies showed similar or greater effect of PI with some visual materials than with verbal material but not with others (Badre and Wagner 2005; Brandon et al. 2003; Postle et al. 2004). In this respect, it appears likely that greater PI was observed with some visual stimuli as a result of a lack of distinctive features between the items of the memory set, leading to decreased discriminability between content-context bindings to recollect in order to resolve PI.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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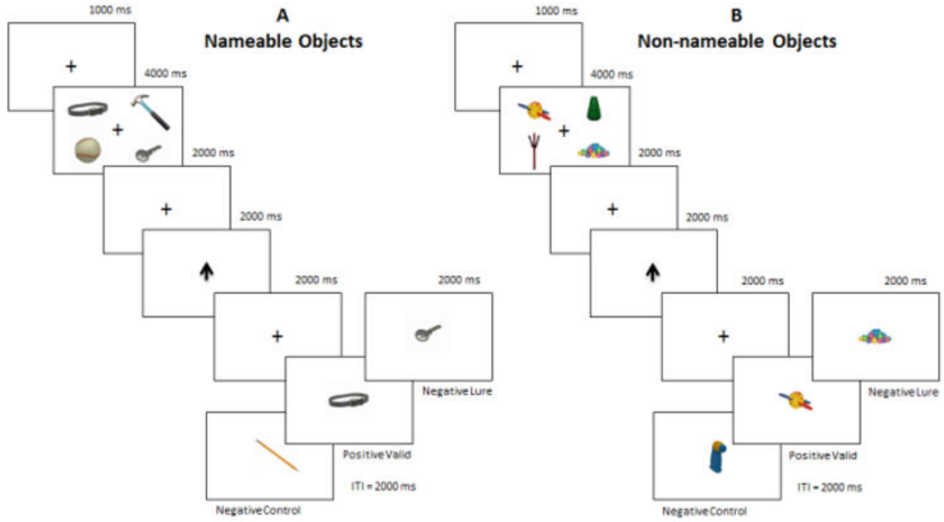

Fig. 1.

Depiction of the visual non-verbal Suppress task. Stimuli are pictures of objects that were validated in Experiment 1 as having either high nameability (left panel) or low nameability (right panel). The three different trial types are illustrated. In positive valid trials, the probe item was in the part of the encoding set that was cued to be remembered (e.g., arrow pointing upwards). In negative lure trials, the probe item was in the part of the encoding set that was cued to be forgotten, while in negative control trials, the probe item was not in the encoding set. Presentation duration is in the upper-right corner of each slide in milliseconds.

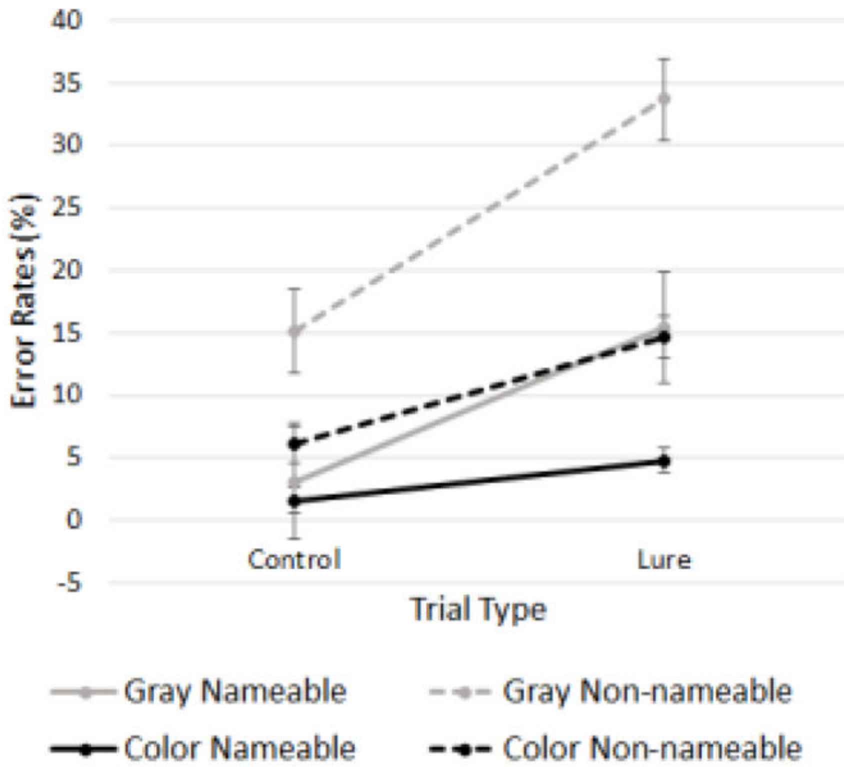

Fig. 2.

Error rates in Control and Lure trials for each condition. Higher error rates in Lure trials relative to Control indicate a significant effect of proactive interference in all conditions. The Lure-Control difference scores were significantly greater in the High Nameability relative to the Low Nameability conditions, and in the Gray relative to Color conditions. Error bars represent ± 1 SEM.

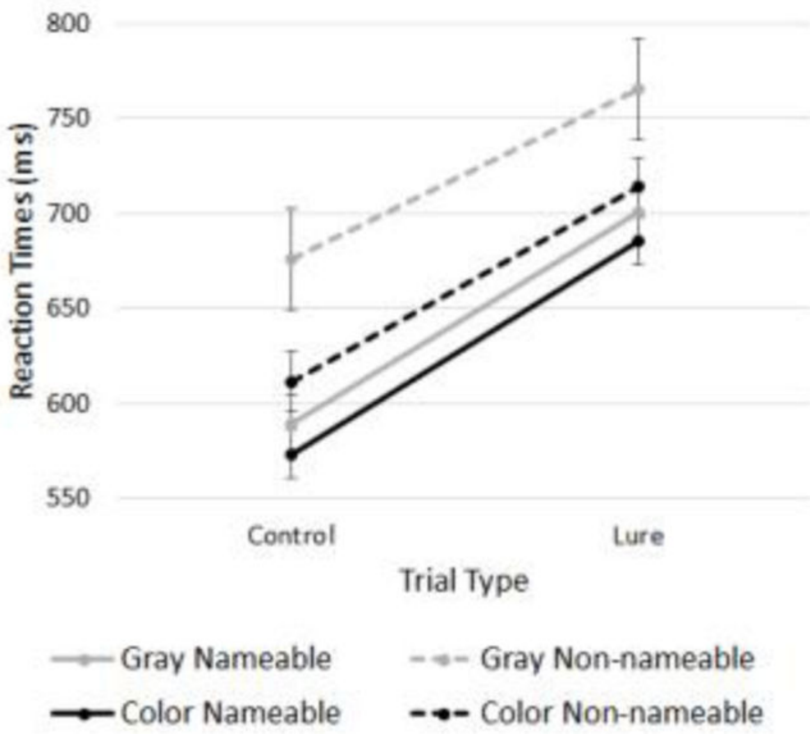

Fig. 3.

Reaction times in Control and Lure trials for each condition. Higher reaction times in Lure trials relative to Control indicate a significant effect of proactive interference in all conditions. Error bars represent ± 1 SEM.

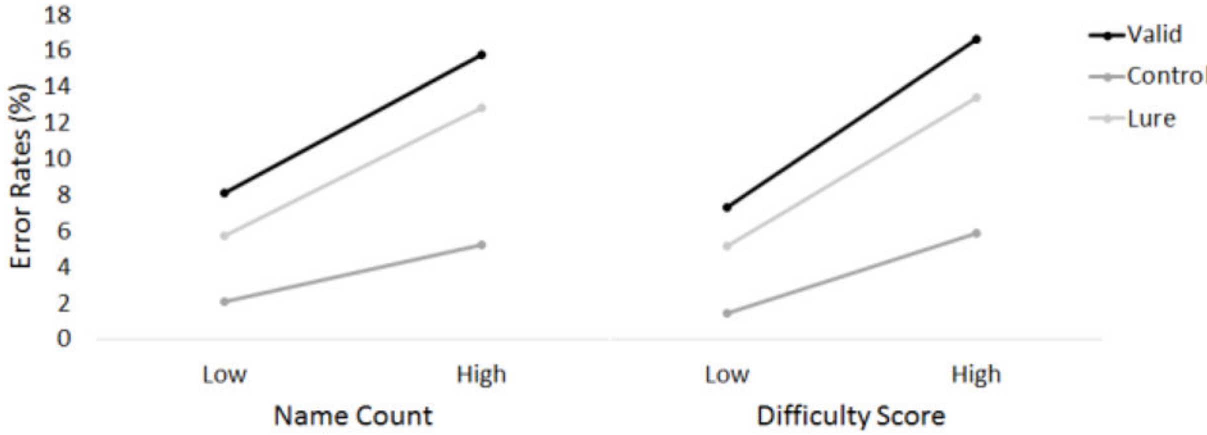

Fig. 4.

Effect of Nameability on ER across Probe Types for Name Count and Difficulty Score. Low and High point estimates were calculated for interactions at ± 1 SD from the mean value of the predictor variables (i.e. Name Count and Difficulty Score, respectively).

Table 1

Descriptive statistics and pairwise comparisons between probe types for ER.

		Descriptive Statistics			Pairwise Comparisons	
Group	**Condition**	**Probe Type**	***M***	***SD***	**Probe Type**	***p***
Gray	Nameable	Valid	13.4	20.2	Valid vs. Control	= .015
		Control	3.0	6.0	Valid vs. Lure	= .498
		Lure	15.5	24.4	Lure vs. Control	= .011
	Non-Nameable	Valid	28.3	23.6	Valid vs. Control	= .001
		Control	15.1	19.1	Valid vs. Lure	= .096
		Lure	33.7	24.3	Lure vs. Control	< .001
Color	Nameable	Valid	7.2	9.4	Valid vs. Control	= .003
		Control	1.6	2.8	Valid vs. Lure	= .115
		Lure	4.8	6.5	Lure vs. Control	= .004
	Non-Nameable	Valid	16.9	17.3	Valid vs. Control	< .001
		Control	6.2	9.8	Valid vs. Lure	= .315
		Lure	14.7	12.7	Lure vs. Control	< .001

Table 2

Descriptive statistics and pairwise comparisons between probe types for RT.

		Descriptive Statistics			Pairwise Comparisons	
Group	**Condition**	**Probe Type**	***M***	***SD***	**Probe Type**	***p***
Gray	Nameable	Valid	609.2	179.7	Valid vs. Control	= .314
		Control	589.4	118.5	Valid vs. Lure	< .001
		Lure	700.4	183.4	Lure vs. Control	< .001
	Non-Nameable	Valid	688.5	158.9	Valid vs. Control	= .621
		Control	676.0	126.5	Valid vs. Lure	= .039
		Lure	765.4	167.2	Lure vs. Control	= .003
Color	Nameable	Valid	584.6	132.5	Valid vs. Control	= .314
		Control	573.3	95.7	Valid vs. Lure	< .001
		Lure	685.6	144.9	Lure vs. Control	< .001
	Non-Nameable	Valid	627.8	150.4	Valid vs. Control	= .337
		Control	611.6	129.6	Valid vs. Lure	< .001
		Lure	713.7	155.8	Lure vs. Control	< .001

Table 3

Statistics of the main effects of Nameability on ER for each probe type and pairwise comparisons of these effects between probe types.

		Main effects			Pariwise Comparisons			
Nameability Measures	**Probe Type**	***b***	***t***	***p***	**Probe Type**	***b***	***t***	***p***
Name Count	Valid	12.55	7.78	<.001	Valid vs.Control	6.82	2.61	< .001
	Control	5.73	2.79	< .01	Valid vs. Lure	0.11	0.04	= .966
	Lure	12.66	6.18	<.001	Lure vs.Control	6.93	2.39	< .05
Difficulty Score	Valid	2.89	9.56	<.001	Valid vs.Control	1.44	2.95	< .005
	Control	1.45	3.78	<.001	Valid vs. Lure	0.13	0.28	= .783
	Lure	2.76	7.22	<.001	Lure vs.Control	1.31	2.41	< .05