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Induced Forgetting of Pictures Across Shifts in Context

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Previous research from our lab has shown that recognizing an object stored in visual long-term memory leads to the forgetting of related objects. Here we ask whether context, an integral aspect to modern models of memory, plays a role in induced forgetting. We manipulated the activated context at test, both externally (e.g., changes in testing room) and internally (e.g., 1 hr and 24 hr later). We found that only interfering with the ability to internally reinstate context after 24 hr eliminated induced forgetting. Thus, we demonstrate that mental context reinstatement plays a role in induced forgetting and specify that models of memory should incorporate internal context reinstatement as an underlying factor of forgetting. We also propose a process model of induced forgetting, discuss limitations of laboratory-based memory tasks, and offer a new term, *induced suppression*, to collectively describe this robust phenomenon.

Public Significance Statement

Context plays a substantial role in many models of recognition memory. In 1 such model, forgetting is entirely due to context. The present article sought to test the hypothesis that changes in contextual retrieval underlie forgetting in laboratory-induced forgetting of pictures of real-world objects. We manipulated both spatial and temporal context and found that forgetting survived changes in space, but not changes in time. Induced forgetting was brought back online when the practice phase, which induces forgetting, was also delayed 1 hr and 24 hr. The elimination of induced forgetting after 24 hr appears to be accounted for by models of forgetting that incorporate a role of context, and difficult to account for otherwise. We conclude by presenting a process model of recognition-induced forgetting and suggest that induced forgetting is better characterized as induced suppression.

Keywords: recognition-induced forgetting, induced forgetting, visual long-term memory, forgetting, context

Supplemental materials: https://doi.org/10.1037/xhp0000928.supp

When we recognize real-world objects using visual long-term memory, we typically assume that we are strengthening the memory representations of those objects. Rarely do we consider the effect of accessing memory representations on our memories of other semantically related objects. However, when we recognize an object, we appear to become less able to remember other objects from the same category (e.g., Maxcey, 2016; Maxcey & Woodman, 2014; Megla et al. 2021). For example, consider a scenario in which you select a number of objects from the same category (e.g., berries on a bush, flowers in a garden) and store those selected objects in

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Stimuli are available on the Open Science Framework (https://osf.io/e4kft/).

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memory until you are able to return to them. When you remember one particular object in the group (e.g., which pumpkin my daughter Paige wanted), the act of recognizing that particular object may actually impair your memory for other stored objects (e.g., which pumpkins my sons Hunter and Henry wanted), making it harder to recognize the objects that you had previously stored in memory.

Output Interference

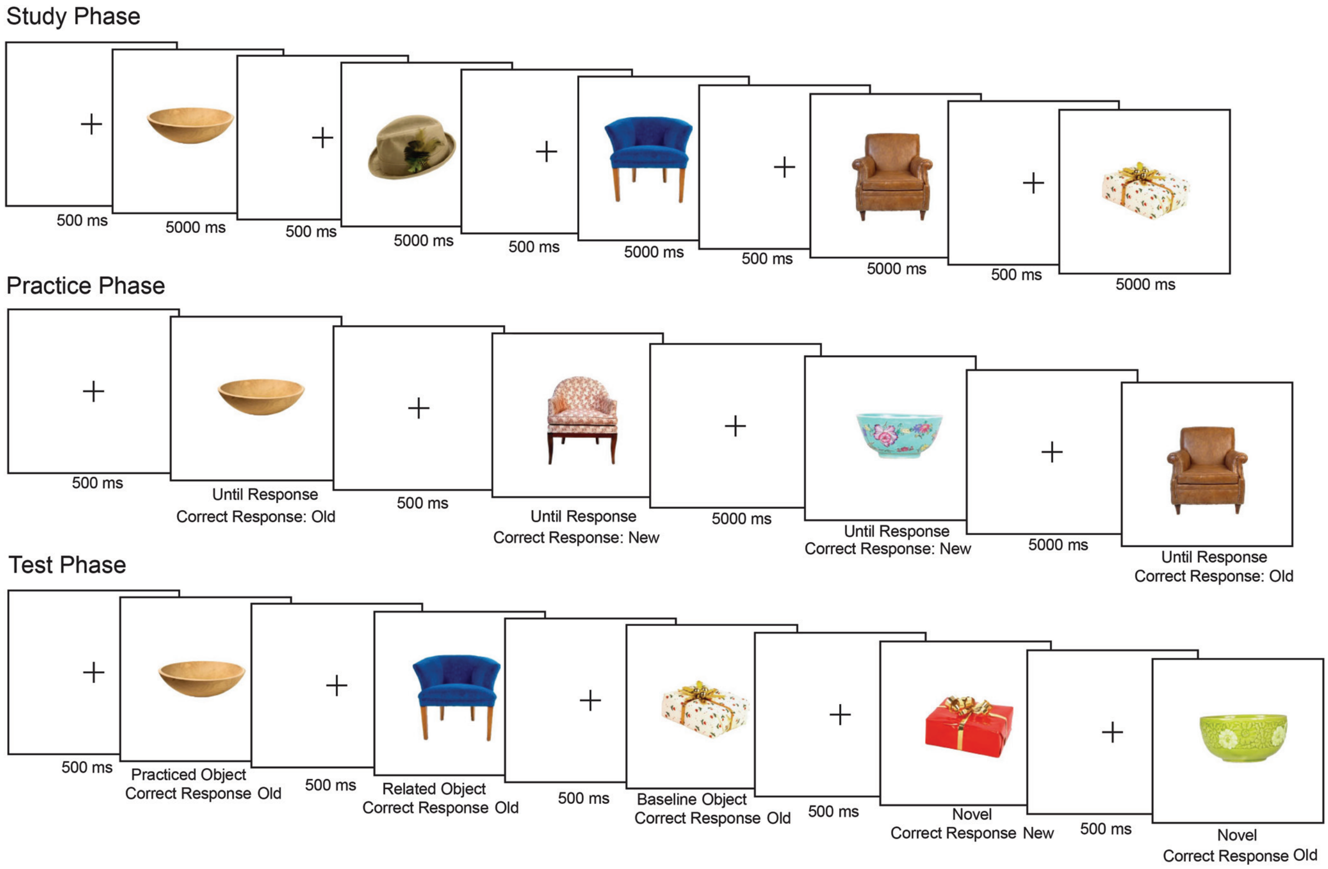
Flavors of access-based forgetting have been studied for many decades. Almost 75 years ago, Helen Peixotto (1947) found that testing memory for syllables hurt recognition of other syllables stored in memory. This negative impact of memory access on subsequently accessed memories (i.e., output interference) has been replicated using both recognition (Criss et al., 2011) and retrieval of word stimuli (Roediger, 1974; Roediger & Schmidt, 1980; Tulving & Arbuckle, 1966), and modeled (Gillund & Shiffrin, 1984). One model suggests that output interference occurs because each encountered item during a memory test is stored, contributing to further interference at retrieval (Criss et al., 2011). Another model argues that retrieval changes the contextual representation, interfering with the accessibility of other memories (Osth & Dennis, 2015; Osth et al. 2018), consistent with evidence that retrieval changes context (Divis & Benjamin, 2014; Jang & Huber, 2008; Sahakyan & Smith, 2014). Indeed, context factors into many models of memory performance (Cox & Shiffrin, 2017; Shiffrin & Steyvers, 1997). According to one model, forgetting is entirely due to context (Dennis & Humphreys, 2001).

Induced Forgetting

Unlike output interference, in which forgetting unfolds across one single memory test, induced forgetting unfolds when accessing memory during one memory test causes forgetting measured in a subsequent memory test (Anderson et al., 1994; Maxcey & Woodman, 2014). The induced forgetting paradigm (see Figure 1, general recognition memory task with picture stimuli) begins with a study phase during which participants are shown pictures of

Figure 1

Example of the Stimuli and Procedure in a Typical Recognition-Induced Forgetting Paradigm



Note. The study phase consisted of 72 items presented sequentially for 5 s interleaved by a 500-ms fixation cross. Participants were instructed to study the visual details of each image for a later memory test. During the practice phase participants were shown half the items from half the categories from the study phase and an equal number of novel objects from the same category. Participants responded by button press to indicate whether the item was an item they studied in the previous phase. During the test phase participants again responded whether an object was old (they had seen it earlier in the experiment) or new (they had never previously seen the object). (See Konkle et al., 2010 for more on the recognition-induced forgetting paradigm.) See the online article for the color version of this figure.

exemplars that belong to larger semantic categories. The second phase is an old–new recognition judgment task where participants are sequentially presented with pictures of objects and asked if they have seen the exact picture previously in the experiment ("old") or whether it is a novel picture ("new"). The old objects presented during this phase create a class of practiced items.

During a final test phase, memory for all objects from the study phase is tested in the same old–new recognition judgment task. The objects belonging to categories that were practiced, but they themselves were never practiced, constitute the class of related items. The objects that did not belong to practiced categories form the class of baseline items.

Practiced objects were shown during both the study and practice phases. It is no surprise that memory for practiced objects is extremely good. Both related and baseline objects were shown only once, during the study phase. Any difference in memory between these two object types can only be attributed to the mechanisms that were in operation during the practice phase.

The typical finding is that memory is best for practiced pictures, intermediate for baseline pictures, and worst for pictures of related objects (Maxcey & Woodman, 2014). The difference between memory for baseline and related objects is the signature induced forgetting effect. The term induced forgetting refers to the idea that retrieving specific representations during the practice phase caused the forgetting of the related representations during the later test phase (Anderson et al., 1994). This is an intriguing effect because neither the related nor the baseline items were practiced, so why is there a difference in memory between these two classes of items?

Context Account Predictions

Despite empirical differences between induced forgetting and output interference, both output interference (Aue et al., 2015) and induced forgetting (Maxcey et al., 2020) result from episodic retrieval tasks and not semantic retrieval tasks, suggesting a shared underlying mechanism. If induced forgetting and output interference are cut from the same cloth, then the same model will account for both effects. Here we test the role of context in induced forgetting, a major contributing factor to many models of memory (Cox & Shiffrin, 2017; Dennis & Humphreys, 2001; Osth & Dennis, 2015; Shiffrin & Steyvers, 1997). The context-reinstatement hypothesis proposes that memories are correctly recalled when the context in which they were encountered is reactivated. Forgetting, then, is due to a failure to reactivate the appropriate context.

In the induced forgetting paradigm, separate contexts are created among the three phases (study, practice, and test phases) because changes in task or even stimuli create context boundaries in memory (DuBrow & Davachi, 2013; Ezzyat & Davachi, 2014). According to the context account, when an object is presented at test, the most temporally recent context in which that object category was encountered is activated. For related objects, this means that the practice phase context is activated because some objects from that category (i.e., practiced objects) were presented in that phase (see Figure 2). The related objects are not found in the reactivated practice phase, leading to poor memory for related objects. The context account makes the following predictions. When the practice phase is reactivated at test, induced forgetting of related objects will occur. However, when the study phase is reactivated at test, induced forgetting will not occur.

One difficulty in testing the context account is that in many models, context is broadly defined. Context could refer to internal context shifts that involve mental time travel to a particular context, while external context shifts involve environmental changes outside of the person's mind. Here we test the context-reinstatement hypothesis in which reactivation of context modulates induced forgetting. Specifically, reactivating that correct context enables effective memory retrieval whereas reactivating the incorrect context leads to forgetting. We ask whether disrupting external, environmental reactivation (Experiments 1a and 1b) or internal reactivation (e.g., mental time travel, Experiment 2) modulate induced forgetting as would be expected if the lack of contextual availability were driving this laboratory-induced forgetting.

Experiment 1a: Context Shifts Across Space Using Different Videos

In Experiment 1a we tested the context-reinstatement hypothesis by reactivating either the practice or study phases using videos. During the study phase each object category was paired with a specific five-second video (e.g., all vases were presented with the escalator video). This created study-video contexts for all object categories. Then at practice, practiced categories were presented alongside a new video (e.g., all practiced vases were paired with the fire truck video). This allowed for two separate contexts to be invoked at test simply by playing either the study video (e.g., escalator video) or the practice video (e.g., fire truck video). The context-reinstatement hypothesis predicts that forgetting of related objects should occur when the practice phase is reactivated (see Figure 2), but not when the study phase is reactivated.

Method

Participants

Participants (N = 76; 48 women, 28 men; M age = 18.8 years) from The Ohio State University who reported normal or corrected-to-normal vision received course credit for participation. Informed consent was obtained prior to procedures approved by the appropriate institutional review board.

Power analyses were performed using G*Power (Faul et al., 2007) to determine the necessary sample size for all reported experiments, using the smallest effect size measured in the original induced forgetting article and typical of literature on recognition-induced forgetting (d_z = 1.376; Maxcey & Woodman, 2014). We estimated that a sample size of 12 participants per condition was necessary to observe recognition-induced forgetting effects with 99% power, given a .05 criterion of significance. The context account predicts null results in certain conditions (i.e., no induced forgetting when the study context is reactivated at test), so we chose a sample size of over triple this estimate (i.e., 38 to 60 participants in each condition) to ensure adequate statistical power.

Figure 2

Illustration of Context-Reinstatement Hypothesis Prediction

Note. When participants are presented with an item at test, they reactivate the most temporally recent phase in which the item's category was encountered. For practiced and related objects, that is the practice phase. However, related objects were not in the practice phase, leading to poor memory for these objects. See the online article for the color version of this figure.

Stimuli

Stimuli were presented using E-prime 2.0 software (Schneider et al., 2012). Participants were seated approximately 80 cm from the monitor. Stimuli subtended approximately 4.6° of visual angle and were drawn from public domain images (i.e., Google images), subdivided into 15 categories with 15 exemplars. Movies were provided by Smith and Manzano (2010). The 5-s videos appeared to be taken with a cell phone, pointed away from the person recording, while doing everyday tasks. These tasks included walking up to a building, walking through a gym, eating in a crowded restaurant, watching an informal baseball game, driving through a parking garage, walking along a sidewalk, or traveling in a car. The videos were randomly paired with each object category.

Procedure

Experiment 1a is a slight modification to the typical recognition-induced forgetting paradigm shown in Figure 1. During the study phase, participants were shown one object at a time on the screen for 5 seconds, interleaved by a 500-ms center fixation cross, until 72 objects had been randomly presented. The 72 objects were randomly selected from 12 categories (e.g., butterfly, mug, vase) with six exemplars drawn from each category.

For all objects, participants were instructed to study the visual details of these objects for a later memory test. They were told that the test would require memory as detailed as "a red bike with a white banana seat." Thus, simply remembering the category "bike" would not help at test.

In the study phase, a 5-s video was shown to the left of fixation with the to-be-remembered object to the right of fixation. The object and video terminated after 5 s. The same video was paired with all objects from the category (e.g., the escalator video was shown with all lamps). This means that each category has its own video during the study phase (i.e., the study video). Following the study phase, participants engaged in a 5-min visual filler task before beginning the practice phase.

The purpose of the practice phase was for participants to practice recognizing half of the objects (three of six) from one half of the 12 categories (six of 12) that were shown in the study phase. The objects were presented on the screen one at a time, until response, and participants performed an old–new recognition judgment task identical to the test phase, consistent with more recent versions of this paradigm (Maxcey, Dezso, et al., 2019, Maxcey, Janakiefski, et al., 2019; Rugo et al. 2017; Scotti et al. 2020). Practiced objects were shown twice (18 objects × 2 trials each = 36 trials), whereas test lures were shown once (36 lures), totaling 72 randomly presented trials with a 50/50 old–new correct response distribution. Practice lures were equally drawn from the same categories as the practiced objects and were never repeated. The specific object categories practiced were counterbalanced across participants, such that objects that were the practice lures were equally often used as the studied objects for other participants. The trials were response terminated and followed by a 500-ms center fixation cross before the next trial.

During the practice phase, all objects from each practiced category were paired with a new video, overwriting the previous study-video context with a new practice-video context. This means that the practiced objects had a new video context (i.e., the practice-video). The video terminated after 5 s, but the object was up until response. A second 5-min break and visual filler task followed the practiced phase.

The test phase images fell into four categories. In three of the categories the objects were old, warranting a "yes" response: practiced objects were shown both during the study phase and practiced in the practice phase; related objects were shown during the study phase and were not practiced in the practice phase, but their category was practiced (e.g., mugs were practiced but not this specific red mug); and baseline objects were shown during the study phase and were not practiced in the practice phase because their entire category was not practiced (e.g., a vase and the category vases was not practiced). The fourth category consisted of new objects, warranting a "no" response: *Test lures* were objects that were never seen before in the experiment. Test lures were drawn from the same categories as the objects during the study phase.

The test trial distribution consisted of 12 practiced, 12 related, and 12 baseline objects, totaling 36 old trials and 36 test lures equally drawn from the same object categories, totaling 36 new trials. All objects were randomly presented during test, regardless of their membership in any of these types of trials. Practice lures from the practice phase were never included in the test phase.

At test, half the participants were in the study-video condition, meaning that the practiced and related objects were presented at test with their corresponding study-videos. According to the context-reinstatement hypothesis, this should eliminate forgetting in the study-video condition context because the study-video reactivated the study phase, which took place before the practice phase (where induced forgetting occurred). The remaining half of participants was in the practice-video condition, meaning that the practiced and related objects were presented with the practice videos. According to the context-reinstatement hypothesis, participants in the practice-video condition context should show forgetting because the practice videos were reactivating the phase where induced forgetting occurred (i.e., the practice phase). The baseline objects were only ever shown during the study phase, so they were always associated with their study-video context. The video was played for 2 s before the object appeared to encourage the participant to watch the video and reactivate that context. The video played for only 5 s, but the object was up until response as in previous experiments. If recognition-induced forgetting occurred in both conditions, then reactivating the study context does not eliminate forgetting, contrary to the context-reinstatement hypothesis.

Data Analysis

The primary dependent variable for our recognition data was d' (Verde et al., 2006), which required values of 1.0 and 0 to be adjusted using $1 - (1/[2N])$ and $1/(2N)$, where N is the number of trials on which the proportion is based (Macmillan & Creelman, 2004). We used mixed-model analysis of variance (ANOVA) with an alpha level equal to .05 and partial eta squared (η_p^2) to measure effect size. Preplanned two-tailed t-tests with an alpha level equal to $\alpha = .05$ were used to determine whether there was a benefit of practice (practiced objects > baseline objects, known as the *practice effect*), a cost related to nonpracticed objects (related objects < baseline objects, known as *induced forgetting*), or a difference between the magnitude of the practice effects and induced forgetting effects across conditions. Bayesian paired samples t tests are reported for all relevant analyses. Reliable t tests are accompanied by Cohen's d measure of effect size. Practice phase accuracy, hit rates and false alarms are presented in the online supplemental material. The instructions to the participants stressed accuracy and not speed so reaction time (RT) was not analyzed.

Bayes Factors

Bayes factors (BF) are immediately interpretable odds, telling us the relative probability of the data under one hypothesis compared with another hypothesis. The Bayesian approach is comparative, such that $BF_{ALT} = 2$ means the alternative hypothesis is two times more likely than the null. This is of particular value here because the null hypothesis is of theoretical interest. Rather than interpreting BF as a means of making decisions about the data, they are best used as a descriptive measure of the evidence.

Results

The mean d' across the types of test objects in the study-video context condition and the practice-video context condition are shown in Figure 3. Contrary to the context-reinstatement hypothesis, both conditions demonstrated reliable induced forgetting, with superior memory for baseline objects compared to related objects in the practice-video context (baseline 1.414, related .765), $t(37) = 7.940$, $p < .001$, $d = 1.288$, $\text{BF}_{\text{ALT}} = 7.10$), and the study-video context (baseline 1.271, related .913), $t(37) = 3.515$, $p = .001$, $d = .570$, $\text{BF}_{\text{ALT}} = 26.78$, conditions. For this and subsequent experiments, see Table S1 in the online supplemental material for evidence that the effects measured using d' are not due to a change in hit rate and false alarm in the same direction (Murnane et al., 1999).

A more measured approach to assessing the role of external shifts of context might assume that certain conditions would reduce, if not eliminate, induced forgetting. To this end, old objects submitted to a 2 (condition: study-video, practice-video) × 3 (object type: practiced, baseline, related) mixed-model ANOVA showed that the magnitude of the practice effect and induced forgetting did not reliably differ across conditions, $F(2, 148) = 2.725$, $p = .069$, $\eta_p^2 = .036$.

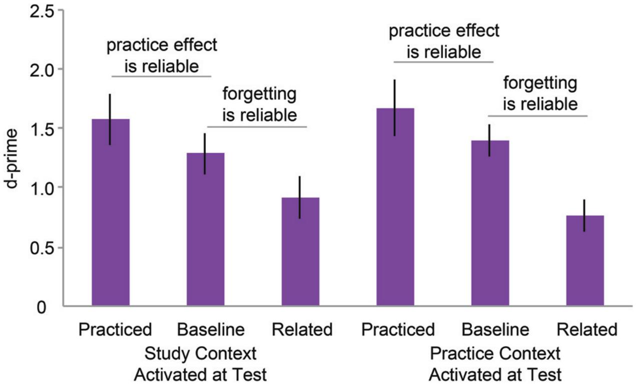
Discussion

We found that the shifts in external context, driven by the presentation of movies that were specific to one phase (i.e., context), did not eliminate induced forgetting. Regardless of which video was presented at test, participants exhibited reliable induced forgetting.

The absence of a significant impact on induced forgetting across conditions raises the possibility that, although videos are known to produce context effects (Smith & Manzano, 2010), including in similar paradigms using words (Jonker et al., 2013), it may be that videos simply became another visual category to the participants in Experiment 1a, possibly because the pictures were not superimposed over the videos. It may also be the case that context plays a larger role in studies employing verbal stimuli due to the many instances outside the laboratory that the participant has encountered each word. This raises the possibility that theories of context have overinflated the role of context in memory due to the nature of the memoranda employed. To determine if a more literal shift in external context (i.e., changing physical rooms) would impact memory in this paradigm using visual stimuli, we implemented such a shift to external context by moving participants to different rooms for each phase of the experiment (Smith et al., 1978).

Figure 3

Experiment 1a Results



Note. d' by object type in the test phase between participants in the study-video context condition and the practice-video context condition. Error bars represent 95% confidence intervals as described by Cousineau (2005) with Morey's correction applied (Morey, 2008). See the online article for the color version of this figure.

Experiment 1b: Context Shift Across Space Using Different Rooms

In Experiment 1b we manipulated external context using a change in physical space. Rather than using movies to create and then reactivate study and practice phases, participants physically moved to a different experimental room between the study and practice phases of the experiment. Participants completed the test phase either in the same room where they completed the study phase or the room where they completed the practice phase. The context-reinstatement hypothesis predicts that forgetting should occur when the participants return to the practice phase room to complete the test phase, but not when participants complete the test phase in the same room where they completed the study phase.

Method

Participants

Forty participants (26 women, 14 men; M age = 19.1 years) from The Ohio State University and 48 participants (37 women, 11 men; M age = 19.1 years) from Vanderbilt University who reported normal or corrected-to-normal vision received course credit for participation. Informed consent was obtained prior to procedures approved by the appropriate institutional review board.

Stimuli

Picture stimuli were identical to Experiment 1a. Movies were not included in Experiment 1b.

Procedure

The procedure was identical to Experiment 1a with the following exceptions. Participants completed the study phase in one of two testing rooms. The rooms differed in size, shape, layout of the furniture, and items within the room (e.g., shelves, tables, binders). The doors to the rooms were located on separate walls and were marked by different signage. Despite both being participant running rooms, they were clearly distinct. To further compel the participants to treat the different rooms as separate contexts, different experimenters staffed each room.

Following the study phase, participants were escorted to a waiting area for a 5-min break. The waiting area was outside both testing rooms, eliminating contextual interference from the testing rooms and creating two clearly distinct contexts for each phase. Experimenters waited in their respective testing rooms, out of view of the participant.

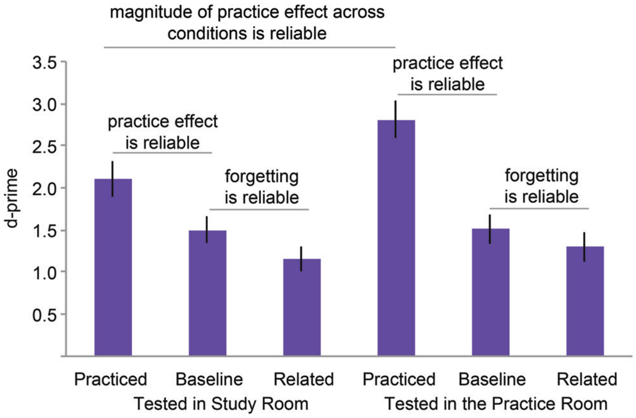
The practice phase was administered by a different experimenter and took place in a second testing room, different than the study phase. These changes created a salient physical differentiation between the contexts of the study and practice phases.

After the practice phase participants were again escorted to the waiting area for another 5-min break. Following the second 5-min break, participants underwent the final phase of the experiment, the test phase. To manipulate context, the test phase was administered in the same room and with the same experimenter as either the study phase or the practice phase. This resulted in a total of four counterbalanced conditions, all of which were randomly administered equally: study in Room A, practice in Room B, test in Room A; study in Room B, practice in Room A, test in Room B; study in Room A, practice in Room B, test in Room B; and study in Room B, practice in Room A, test in Room A. In the first two of these conditions, the study phase context was reinstated in the test phase as the study and test phases were administered in the same room. The context-reinstatement hypothesis predicts both that recognition-induced forgetting should be eliminated when the context in which forgetting does not occur (i.e., the study phase) is reactivated at test, and that recognition-induced forgetting should persist when the context in which forgetting does occur (i.e., the practice phase) is reactivated at test.

Results

The mean d' across the types of test objects in each condition is shown in Figure 4. Recall that the motivation for Experiment 1b was to implement a potentially more robust external context manipulation. To assess whether this context manipulation worked, we ran a 2 (condition: study room, practice room) × 3 (object type: practiced, baseline, related) mixed-model ANOVA, resulting in a significant interaction, $F(2, 172) = 8.264$, $p < .001$, $\eta_p^2 = .088$. Demonstrating that the context manipulation was effective, the difference in magnitude of the practice effect (practice-baseline) between study room (.493) and practice room (1.038) conditions was reliable, $t(86) = 3.444$, $p < .001$, $d = .734$, $BF_{ALT} = 33.229$. Superior memory for practiced items when participants were tested in the practice rooms demonstrates that the context manipulation was effective.

Figure 4
Experiment 1b Results



Note. d' by object type in the test phase of participants tested in the study room and the practice room. See the online article for the color version of this figure.

Having shown that the context manipulation was effective, we next turned to the question of the impact of context on induced forgetting. Contrary to context account predictions, both conditions demonstrated reliable induced forgetting. Memory for baseline objects was reliably higher than memory for related objects when participants were tested in the practice room (baseline 1.488, related 1.280), $t(43) = 2.351$, $p = .023$, $d = .354$, $BF_{ALT} = 1.919$, and when participants were tested in the study room (baseline 1.499, related 1.147), $t(43) = 3.487$, $p = .001$, $d = .526$, $BF_{ALT} = 26.39$. Further, the size of induced forgetting (baseline-related) between study room (.352) and practice room (.209) conditions was not reliably different, $t(86)= 1.066$ $p = .289$, $d = .227$, $BF_{NULL} = 2.725$.

Discussion

The results of Experiment 1b showed that the context manipulation was effective because the practice effect was larger when participants' memory was tested in the practice room. Experiment 1b did not support the predictions of the context reinstatement hypothesis across shifts of space. Specifically, reactivating the distinct physical contexts of the study or practice phases at test did not have a reliable impact on forgetting.

It may be the case that context effects are only present when participants are tested in entirely novel contexts. Murnane and Phelps (1994) found an effect of context on recognition memory only when the different context was an entirely new context, not previously encountered in the experiment. Their contexts were defined by location on the screen, color of the font, and color of the background. While their context manipulations were likely less robust contexts than entirely different rooms (as in Experiment 1b), they did have a condition in which old items could be tested in novel contexts (defined as a combination of foreground color, background color, and spatial location on the screen) unlike Experiment 1 in which there was never an entirely novel context for testing.

It may also be that recognition tasks, such as the one used in the induced forgetting paradigm, are simply impervious to shifts of external context. Godden and Baddeley (1975) performed their well-known scuba diver experiment, in which divers learned lists of words on land or under water and then remembered the words in the same or opposing context using both a recall and a recognition task (Godden & Baddeley, 1980). Although they found an effect of external context on memory using recall, when they used a recognition task, they found no effect of external context. They interpreted this result as indicating that external context has an arbitrary relationship with the stimulus, contributing no additional useful information in the face of the presentation of the physical stimulus in a recognition task.

Given the vexed history of external shifts of context on recognition memory (Murnane & Phelps, 1993), it may be that induced forgetting survived these extremely robust shifts of external context because participants were mentally time traveling to the most temporally recent context in which the objects were encountered, regardless of the room of testing. Indeed some modern theories of context and memory include an aspect of mental time travel

(Polyn et al., 2009). Perhaps instead of ruling out the context-reinstatement hypothesis, induced forgetting persisted in Experiment 1 because participants shifted internal contexts, an explanation we address in Experiment 2.

Experiment 2: Context Shift Across Time

Context-reinstatement models of forgetting suggest that forgetting is a consequence of difficulty reinstating the context in which the original memory was encoded. In Experiment 1 we found that manipulating external context did not eliminate induced forgetting. The robustness of induced forgetting against external context change suggests two possibilities. One possibility is that induced forgetting is not caused by the failure to reinstate proper context at the time of retrieval. Alternatively, induced forgetting may be selectively sensitive to the shift of internal context but not to that of external context.

In Experiment 2 we tested the hypothesis that induced forgetting is eliminated by internal shifts of context through a delay interval, while holding external context constant. If induced forgetting survives the delay, then context-reinstatement models do not appear to explain induced forgetting through either external or internal shifts of context. If induced forgetting does not survive the delay, then context-reinstatement models of induced forgetting should emphasize internal shifts of context.

Manipulating context through a delay is the only guaranteed way to manipulate internal context without measuring brain activity. One advantage of this manipulation is that the forgetting literature debates whether displacement of information (McGeoch, 1932) or the passage of time (Hintzman, 2004) underlies forgetting, and the introduction of a 24-hr delay where participants leave the laboratory for an entire day employs both. Specifically, we delayed the test phase such that participants were engaged in other mental tasks for an hour (e.g., watching Netflix) or even experienced an entire day outside the laboratory (e.g., leaving the laboratory for 24 hr). Logically studies that suggest context changes across manipulations within a single experiment (Jonker et al., 2013) would certainly agree that context changes many times throughout the course of a 60-min or 24-hr period. Such time-dependent changes have been employed in studies of induced forgetting of words (Abel & Bäuml, 2014; Carroll et al. 2007; Chan, 2009; MacLeod & Macrae, 2001; Saunders & MacLeod, 2002) and are a type of contextual fluctuation that contribute to forgetting in many models of memory (Mensink & Raaijmakers, 1988).

In Experiment 2 we manipulate internal context reinstatement by increasing the delay between practice and test such that internal reactivation of context would be more difficult. If the context account is correct and forgetting of related objects is due to erroneously reactivating the practice phase instead of the study phase, then extending the time between practice and test should blur the boundaries between study and practice, eliminating forgetting.

Method

Participants

There were 60 participants (33 women, 27 men; *M* age = 19.58) from The Ohio State University in the 60-min delay condition. In the 24-hr delay condition, there were 49 participants (31 women, 18 men; *M* age = 20.3) from The Ohio State University and 10 participants (three women, seven men; *M* age = 18.9) from Vanderbilt University. One participant did not return for the second day of testing and their data were not included.

Procedure

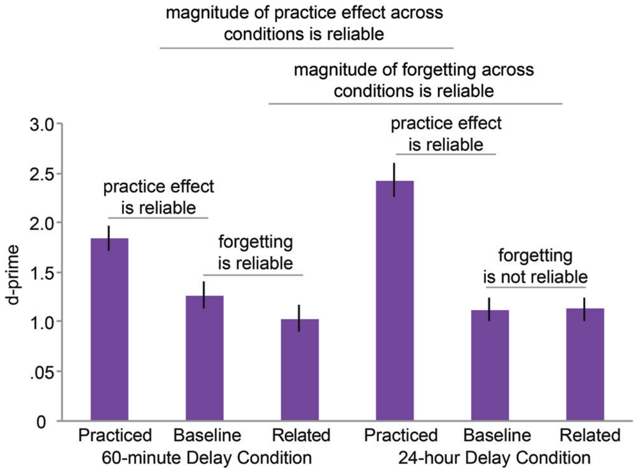
The procedure was identical to Experiment 1 with the following exceptions. First, there were no videos paired with the presentation of objects (Experiment 1a) and there were no room changes between phases (Experiment 1b). Second, we introduced a longer delay between the second (practice) phase and the third (test) phase of the experiment. In the typical induced forgetting paradigm, the practice phase is followed by a 5-min delay before test. In Experiment 2, the delay between study and practice was 60 min or 24 hr. In the case of the 60-min delay, participants were instructed to bring something to entertain them during the break (e.g., doing homework, watching Netflix, responding to emails). In the 24-hr delay condition, participants were notified that there were two experimental sessions, separated by exactly 24 hr. They completed the first two phases on Day 1, left the laboratory for 24 hr, and then returned on Day 2 to complete the test phase. The objects used and stimulus presentation parameters were the same across the two delay conditions.

The logic behind extending the delay between the practice and test phases, rather than the delay between the study and practice phases, was because the practice phase is what causes forgetting. It is the recognition practice that induces forgetting (hence the term induced forgetting). Here we aimed to measure the transient nature of induced forgetting, requiring that we first induced forgetting, and then manipulated the duration of the delay.

Results

In the 60-min delay condition (Figure 5), both the practice effect (baseline 1.252, practiced 1.982), $t(59) = 8.380$, $p < .001$, $d = 1.082$, $\mathrm{BF}_{\mathrm{ALT}} = 7.323 \times 10^{8}$, and induced forgetting (baseline

Figure 5
Experiment 2 Results



Note. From the 60-min and 24-hour delay conditions. d' by object type in the test phase. See the online article for the color version of this figure.

1.252, related 1.028), $t(59) = 2.733$, $p = .008$, $d = .353$, $BF_{ALT} = 4.128$, were reliable. In the 24-hr condition, the practice effect was reliable (baseline .863, practiced 2.025), $t(58) = 14.042$, $p < .001$, $d = 1.828$, $BF_{ALT} = 1.872 \times 10^{17}$, but induced forgetting was not reliable (baseline .863, related .907), $t(58) = .614$, $p = .9542$; d = .080, $BF_{NULL} = 5.867$. The difference in the size of induced forgetting was reliable across the 60-min delay (.224) and 24-hr delay (.044), $t(117) = 2.453$, $p = .016$, d = .450, $BF_{ALT} = 2.568$, driven by a decrease in forgetting after 24 hr. These results show that induced forgetting was reliable for the 60 min delay, but was eliminated at the 24-hr delay.

Discussion

Recall that based on the assumption that context changes across time, by increasing the time between the practice and test phases, we expected to blur the lines between study and practice contexts. This should make the specific reactivation of the practice context more difficult, eliminating forgetting. However, induced forgetting was present after 60 mins. It may be that a 60-min delay during which participants remained in the laboratory is not a sufficient delay to blur the boundaries of the two contexts that might be reactivated during this task. Induced forgetting is eliminated when the ability of participants to mentally time travel to reinstate internal context is bolstered by increased time and thus increased interference. The present study is critical to models of memory and forgetting that apply to all stimuli (i.e., visual and verbal) because it is only the second demonstration of a manipulation that can eliminate induced forgetting of pictures (Maxcey et al., 2020). These results suggest that internal context shifts drive induced forgetting, informing our process model proposed in the General Discussion.

General Discussion

Over the last several years, evidence for induced forgetting of pictures (Maxcey & Woodman, 2014) has shown that visual memory is prone to impairments similar to those shown with words (Anderson et al., 1994), despite evidence that memory for pictures is superior to memory for words (Hockley, 2008; Paivio & Csapo, 1973). Induced forgetting is also striking because it appears cognitively impenetrable, as it occurs even in the face of awareness of the effect (Maxcey, Dezso, et al., 2019), is invoked by both recognition of old objects and rejection of new objects (Fukuda et al., 2020), and occurs following instructions to simply restudy pictures rather than instructions to recognize them (Maxcey, Janakiefski, et al., 2019).

Currently the most theoretically important question surrounding induced forgetting is arguably *what is the underlying mechanism driving such induced forgetting effects?* The relationship between induced forgetting and episodic memory (Maxcey et al., 2020) supports that a likely component of forgetting is context. Context, broadly defined, is presumed to play a role in episodic memory (Tulving, 1983) with models of memory suggesting context reinstatement underlies both remembering and forgetting (Cox & Shiffrin, 2017; Dennis & Humphreys, 2001; Osth & Dennis, 2015; Shiffrin & Steyvers, 1997). Here we provide two robust methods of external context reinstatement, by pairing objects with specific video contexts (Experiment 1a) and manipulating the room of learning and testing (Experiment 1b). We found that such robust external shifts of context do not eliminate induced forgetting.

We next asked if employing internal shifts of context would influence induced forgetting. If participants were internally shifting context through mental time travel in Experiment 1, this would explain the persistence of forgetting (Jonker et al., 2013). We found support that internal context shifts underlie induced forgetting. Induced forgetting was eliminated by interfering with participants' ability to effectively mentally time travel through a 24-hr delay between practice and test. These delay results are not explained by shifts in external context because participants returned to the same experimental testing room and forgetting survives shifts in external space, as demonstrated by Experiment 1.

How Can Existing Models Account for These Results?

It is not immediately obvious how existing models that account for induced forgetting through inhibition, familiarity, list length, recognition by recall, or trace updating clearly predict forgetting will be eliminated by 24 hr. Whereas neither retrieval-induced (MacLeod & Macrae, 2001) nor recognition-induced forgetting survive a 24-hr delay, the practice effect remains in both cases. These findings necessitate the existence of two dissociable memory activations triggered by retrieval practice and lead us to propose the following process model of induced forgetting.

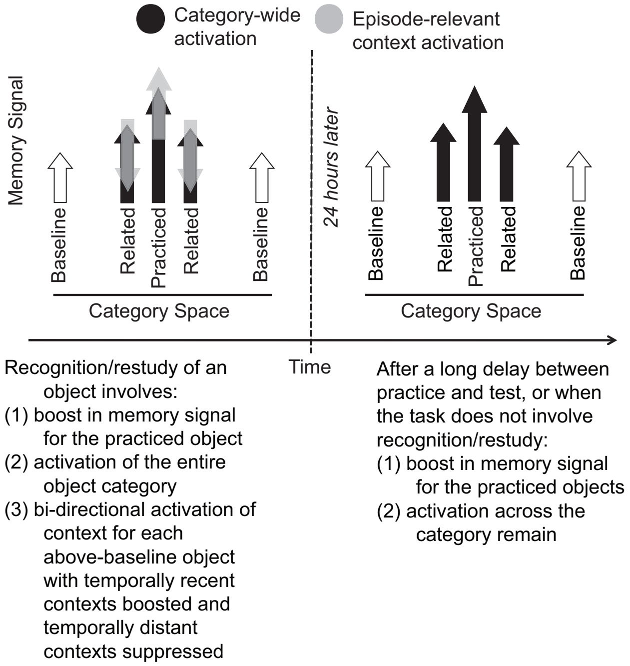
Proposed Process Model

Existing studies of induced forgetting have demonstrated that forgetting is eliminated in two ways. First, induced forgetting is eliminated through replacing the typical episodic memory practice phase task (i.e., old–new recognition judgment: "Have you seen this object?") with a semantic memory task (e.g., size judgment: "Is this object bigger than a loaf of bread?"; Maxcey et al., 2020). This means that a process model of induced forgetting must show forgetting in a task referring participants to a particular episode, and also show that forgetting does not occur in a task when participants are not referred back to a particular episode. Notably, when induced forgetting does not occur in semantic memory tasks, memory for related objects tends to be slightly above baseline. This finding is also explained in the following proposed process model. The second condition under which forgetting is eliminated is when imposing a 24-hr delay between practice and test, as shown here (Experiment 2).

We propose that when practice and test occur close in time (i.e., within 1 hr), the representation of each object (see Figure 6, arrows) is tightly coupled to the category cue (see Figure 6 where category objects are clustered together in category space). This means that when a memory-test probe is presented to our observers in an old–new recognition judgment task the following sequence of operations unfolds. First, activation, perhaps in the form of similarity signals (Nosofsky et al., 2011), is summed across representations in memory and the test probe, boosting the memory signals for objects from the same category as the probe, creating competition among within-category representations. These summed similarity signals create an activation mound across categorically related representations (see Figure 6, black arrows). Second, when able to access the rich context in which the object category was most recently experienced, bidirectional

Figure 6

Process Model of Induced Forgetting



Note. This figure illustrates how two opposing memory processes play out when the practice and test phases are closely coupled in time (left panel) and when there is a longer delay between practice and test (right panel). Episodic-relevant context activation (gray) and category-wide activation (black) both contribute to memory test performance when the practice and test are closely coupled in time and the learning episode can be reinstated. These two opposing mechanisms result in induced forgetting of related objects. When the time between practice and test increases, it becomes more difficult to retrieve episode-relevant context (gray) information. Category-wide activation (black) remains, driving memory test performance.

episode-relevant context activation (see Figure 6, gray arrows) operates over the activation mound in category space. As predicted by the context-reinstatement hypothesis (see Figure 2), this leads to a boost in the memory signal for the practiced object and suppression of related objects not found in the most temporally recent context. Finally, participants make button press responses based on the magnitude of this combined activation.

Over time, the episodic experience of seeing more objects of one category relative to the other object categories becomes blurry, as previous temporal context becomes harder to access with more interference (Peterson & Peterson, 1959). This means that when an object probe is presented after 24 hr, the episode-relevant context activation is weakened or gone (see Figure 6, right panel). At 24 hr, participants are left with the boost in memory signal for the practiced object, due to previous repetitions of the practiced object and the activation across the category. This reorganization of memory activation after 24 hr is consistent with changes in hippocampal representations after 24 hr (Lee et al., 2019) and models proposing that episodic, context-dependent memories transform to more semantic versions over time (Sekeres et al., 2018; Winocur & Moscovitch, 2011). This model can even account for the slightly increased practice effect after 24 hr, if one assumes a release from lateral inhibition that was operating over episodic memory associations.

An alternative explanation of the same pattern of results may simply be found in the inherent properties of neurons in the temporal lobe. Specifically, the tuning function of neurons in the temporal lobe, measured in spikes per second, can elicit below baseline (relative to spontaneous firing rate) responses (Kutter et al., 2018; Rolls, 1984; Thome et al. 2012). Therefore, when presenting one neuron with a yellow butterfly, the yellow butterfly may elicit 50 spikes per second while a blue butterfly may elicit −10 spikes per second below baseline. Upon every presentation of an object, across cells in the temporal lobe, there is a mound of activation for that item that includes neighboring suppression. Typically, these mounds will average out due to interference, which may explain why we do not find forgetting at 24 hr. Contrarily, the mounds must remain stationary, keeping the below-baseline activity over the same representations, to prevent averaging out from the typical interference. This could be accomplished through repeated presentation of objects in the practice phase of the induced forgetting paradigm. This tuning function account may explain forgetting in both the present study and previous work showing that simply repeated presentation of items also leads to forgetting (Maxcey, Janakiefski, et al., 2019).

Induced Forgetting or Induced Suppression?

We have been using the term *induced forgetting* to refer to the empirical result of worse memory for related objects relative to baseline objects. Here we show that empirical result does not persist for 24 hr. Given the temporary nature of this effect, *induced suppression*, rather than induced forgetting, is a more accurate description of this effect.

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