General knowledge and detailed memory benefit from different training sequences

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Abstract

Real-world learning contexts sometimes require the use of general knowledge, whereas others depend on recalling detailed information about individual events. By combining category learning with trial-unique source information, we examined how different learning sequences (blocked vs. interleaved) impact the acquisition of generalized (category-level) and detailed (exemplar-specific) knowledge. Participants were trained to identify paintings by different artists, half of which were studied in a sequence blocked by artist and the remainder interleaved between artists. Participants were tested on general knowledge (category induction) and detailed memory (source recall), both immediately after learning and a 1-week delay. We found that interleaved learning improved general knowledge, but blocked learning improved detailed memory. Furthermore, we found that general knowledge remained stable whereas detailed memory performance declined after a delay. Our results indicate that optimal training conditions differ based on the goals of learning such as enhancing general knowledge or improving memory of individual event details.

Keywords: learning, memory, induction, category-learning, general knowledge, source memory, retention, sequencing, blocked, interleaved, differentiation

In real world learning contexts, there are times when we need to remember specific details of an event, and others when we need to use our general knowledge. Acquisition of episodic details and general category knowledge have typically been studied separately; however, in natural learning contexts, it is often possible to extract both general knowledge and specific details from the same learning event. For instance, an art student touring various museums may encounter the *Doni Tondo* for the first time and use her general knowledge of Renaissance artist styles to make an educated guess that the work was painted by Michelangelo. Additionally, she may encode a specific memory of this experience of having seen the *Doni Tondo* at the Uffizi Gallery in Florence. Thus, an open question might be how one could optimize learning to improve acquisition and retention of these seemingly distinct types of information (memory for specific episodes vs. general knowledge).

Studies on category learning have revealed that category induction can be optimized by manipulating the order or *sequence* in which category exemplars are presented during study (Birnbaum, Kornell, Bjork, & Bjork, 2013; Carvalho & Goldstone, 2015; Kang & Pashler, 2012; Kornell & Bjork, 2008; Noh, Yan, Bjork, & Maddox, 2016). In particular, studies using real-world stimuli find that categories are better learned when category exemplars are interleaved (intermixing category exemplars across categories) during study rather than blocked together by category (Birnbaum, Kornell, Bjork, & Bjork, 2013; Kang & Pashler, 2012; Kornell & Bjork, 2008; Rozenshtein, Pearson, Yan, Liu, & Toy, 2016). This finding was somewhat counterintuitive, as blocking exemplars by category may better allow one to notice the similarities between exemplars that define the category (Kornell & Bjork 2008).

The leading theory that has been proposed to explain the interleaving benefit for categorization is the *discriminative-contrast hypothesis*, which states that interleaving highlights across-category differences and improves category discriminability by juxtaposing exemplars from different categories. According to this theory, what is more important than learning similarities that define a category is to learn the differences that differentiate between categories. Consistent with this theory, research has found that interleaving is beneficial to category learning specifically when it promotes discriminative contrast (Birnbaum, Kornell, Bjork, & Bjork, 2013; Kang & Pashler, 2012; Carvalho & Goldstone, 2015; Carvalho & Goldstone, 2017). In fact, Birnbaum, Kornell, Bjork, & Bjork (2013) examined the influences of both temporal spacing (spaced vs. massed practice) and study sequences (blocked vs. interleaved schedules) and found that temporal spacing was advantageous when it did not interfere with discriminative processes (i.e., in conjunction with a blocked sequence), but was harmful when it interrupted the juxtaposition of interleaved categories. Thus, by intermixing exemplars from different categories, one can improve general category knowledge by highlighting the differences between categories and therefore enhance the ability to discriminate among them.

Discrimination and differentiation also play an important role in memory (Criss & Koop, 2015). Studies suggest that differentiation is a fundamental mechanism that underlies human memory—specifically, the more that is known about an item in an episode, the less similar and confusable it is with other episodes (Shiffrin & Steyvers, 1997; McClelland & Chappell, 1998). Relatedly, the *Von Restorff effect* highlights the role of distinctiveness on memory encoding and suggests that features that differ from

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others amongst a relatively homogenous set of stimuli are more likely to be remembered (Hunt, 1995). This may suggest that to enhance memory, one could juxtapose similar events to highlight their distinct features and improve memory for the individual events. A blocked sequence that juxtaposes similar category exemplars may be optimal then for facilitating the discrimination process by highlighting subtle differences amongst similar stimuli and enhancing memory for specific event details.

Our theory expands on the discriminative-contrast hypothesis in category learning to accommodate different types of learning. We argue broadly that sequencing promotes local contrast and differentiation between adjacent trials. Thus, blocked vs. interleaved sequences during category learning may help learners to better discriminate at different levels of knowledge. The optimal sequence for learning then, would depend on the learning goals. An interleaved schedule allows learners to contrast exemplars between categories, which allows for improved discrimination at the *category-level*. On the other hand, a blocked schedule may allow learners to differentiate within a category and promote discrimination at the *exemplar-level*. In fact, perhaps this exemplar-level (within-category) discrimination afforded by blocking, while improving detailed memory by highlighting distinctiveness, is what hinders learners from optimally abstracting and forming general knowledge about categories presented in a blocked schedule by further differentiating the exemplars from one another and hindering the abstraction of conceptual information that is shared amongst them. Therefore, we predict that while interleaved sequences should facilitate the acquisition of general (category) knowledge by promoting category-level differentiation, blocked sequences should enhance memory for details by highlighting distinct features

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amongst similar category exemplars at the item-level. We developed a paradigm that tests this theory directly by simultaneously measuring the acquisition of knowledge at various levels of specificity from more general knowledge to detailed recognition.

The current study uses a learning paradigm adapted from Kornell & Bjork (2008) to investigate the effect of different learning schedules (blocked vs. interleaved) on the acquisition and retention of general knowledge and memory for individual event details. Participants learned to categorize example paintings from a number of unfamiliar artists (Figure 1). Each individual painting was also paired with a unique location (real world landmarks) during learning. At both an immediate and a one-week long interval, we tested acquisition of general knowledge using an induction paradigm, in which participants categorized new paintings not seen during the original training. Detailed memory was tested by asking participants to perform source memory judgements, in which they remembered the location associated with individual paintings. We hypothesized that induction performance would be greater in the interleaved learning condition, whereas detailed memory performance would be superior in the blocked condition.

Experiment 1: Determining optimal learning schedules for general knowledge and detailed memory

Experiment 1 manipulated the presentation sequence—blocked or interleaved—in which participants studied category exemplars to examine its effects on both immediate and delayed tests of general knowledge and detailed memory. Participants completed two experimental sessions that were 1 week $\pm$ 1 day apart (Figure 1). The

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first session consisted of the learning phase as well as immediate tests of general knowledge and detailed memory. The second session assessed both general knowledge and detailed memory after a delay, using a set of test items unique from those used for the immediate memory tests.

Method

Participants. Participants were recruited from the University of Texas at Austin's Psychology undergraduate subject pool. Participants received course credit for their participation in the study. There were 51 participants in Experiment 1 (age = 18-31 years, $M \pm SD = 19.96 \pm 2.96$, 16 Male). The target sample size was determined from a power analyses conducted on the results from Kornell & Bjork (2008). The power analysis revealed that a sample size of 8 was required to observe the interleaving benefit on induction performance, our test of general knowledge. However, in the present study, we further wanted to assess an interaction of learning schedule on general knowledge and detailed memory; thus, we increased our target sample size well beyond that identified by our initial power analysis. After an initial pilot of our task design ($n = 10$), we extrapolated that approximately 50 participants would be necessary to assess an interaction between learning schedule and memory test, given the difficulty of the source memory task that required individuals to remember the unique location paired with each painting. Of the 51 participants, data from one participant was excluded for technical issues with the software that arose in Session 2, leaving a final sample size of 50 for the target analysis (age = 18-31 years, $M \pm SD = 20 \pm 2.98$, 16 Male).

Materials. The images used for the experiments were 18 landscape paintings by each of 12 artists (Grossman, Grote, Hawkins, Juras, Lindenberg, McKinley, McNamara, Petro, Schlorff, Schwartz, Walter, and Wexler). Six unique paintings by each artist were used for the learning and memory test phases and six unique paintings were used for each generalization test (immediate and delayed). Paintings were cropped and resized to 500 x 333 pixels. In addition, we used images of 72 famous landmarks (36 natural and 36 manmade images cropped and resized to 333 x 333 pixels), each of which were paired with a unique painting during the learning phase. The landmark images also served as memory probes and choices during the source memory tests.

Procedure. *Session 1 learning.* During each learning trial, participants saw one of the paintings next to an image of a unique location at the top of the screen (Figure 1b). Participants were told that their goal was to learn each artists' painting style, and that in a later phase, they would be shown a new painting and would have to identify the artist based on what they learned about each artists' style. To facilitate learning the artists' style, participants were asked to select the name of the artist to which each painting could be attributed from all twelve possibilities (presented as options at the bottom of the screen). Participants had up to 10 seconds to make their selection. After making their choice, the correct artist's name was presented as feedback (2 s) before moving on to the next painting-landmark pair. Importantly, across learning, the screen position associated with each artist's name was shuffled trial-to-trial to avoid spatial

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response biases during learning. During the learning phase, participants were exposed to 6 unique paintings for each of the 12 artists.

Each painting was paired with a unique landmark during learning. Participants were instructed that the landmarks corresponded to the nearest recognizable location where the painting could be found (e.g., a painting shown next to a picture of the Washington Monument indicated that the painting was located near that landmark). Participants were told to use the landmarks as an aid for learning but were not explicitly instructed that they would be tested on the associations between paintings and landmarks. Assignment of landmarks to individual paintings was determined randomly for each participant.

To assess the effects of different learning sequences on the acquisition of general (category) knowledge and detailed (source location) memory, we presented the 12 artist categories using one of two possible sequence types: blocked and interleaved. Half of the artists (determined randomly for each participant) were assigned to each sequence type. For blocked sequences, all six paintings from one artist were presented sequentially. For interleaved sequences, one painting from each of six artists were presented sequentially. In both types of sequence, the same set of six paintings were shuffled and repeated a total of five times. The six blocked sequences (each with six paintings from a unique artist) and six interleaved sequences (each with one unique painting from the same six artists) were presented to each participant in a counterbalanced order: BIIBBIIBBIIB or IBBIIBBIIBBI.

Generalization Test

After the training phase, participants were tested on the general category-level knowledge they acquired during training. During the generalization test (Figure 1, “Generalization Test”), participants were shown 72 new paintings (6 new paintings per artist) and asked to identify the correct artist based on what they learned about each artist’s painting style during the training phase. Participants were shown a painting and had up to 15 seconds to select amongst the 12 artist name options. After participants made their selection (or after 15 seconds), they were shown the correct artist name for 2 seconds before moving on to the next painting. The 72 test trials were pseudo-randomly presented as six blocks of 12 paintings, with each block consisting of one painting from each artist presented in a random order.

Detailed Recognition Test

After the generalization test, participants were tested on their memory for specific details presented during the training phase. In the detailed recognition test (Figure 1, “Detailed Recognition Test”), participants were asked to select the location that was paired with specific paintings that were studied in the training phase. Participants were shown a painting and asked to identify the location of the painting (i.e., the landmark that was paired with that painting during training). Participants were tested on half of the paintings they studied during the training phase (the other half was reserved for the retention test a week later) without any feedback. For each of the 36 tested paintings, participants had 15 seconds to choose amongst 6 previously seen landmarks. The paintings for this phase were randomly selected (3 studied paintings per artist) and presented in a pseudo-random order across three blocks, with each block consisting of one painting from each artist presented in a random order. The

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response choices for each painting were landmarks that were paired with paintings by the same artist during training, which made the detailed recognition test highly specific and particularly difficult, as learners had to remember the specific painting's location and could not use general category-level information to eliminate any of the landmark options provided.

General Recognition Test

After the detailed recognition test, participants then completed a more general test of memory. The general recognition test differed from the detailed recognition test in that participants were asked to identify the artist associated with a given location from the training phase, without having to recall the specific details of the painting that was associated with that location. During the general recognition test (Figure 1, "General Recognition Test"), participants were shown a previously studied landmark and asked to remember the name of the artist whose painting was located at that landmark. Participants were tested on the 36 landmarks that were paired with the paintings tested in the previous phase. The 36 landmarks used were presented in a pseudo-random order, without feedback, across three blocks, with each block consisting of one painting from each artist presented in a random order. Participants were shown a picture of a landmark and had up to 15 seconds to select from 12 artist name options to make their choice. While this general recognition test still probes memory, it is less dependent on remembering the specific details of any individual painting. Thus, the general recognition test serves as an easier and more general test of memory relative to the detailed recognition test.

Tests of knowledge retention

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Participants returned one week later and completed delayed tests of generalization, detailed recognition, and general recognition. The delayed tests were identical to the immediate tests in their structure (e.g., number of trials, timing, shuffling, etc.). During the generalization test, participants were tested on 72 new paintings (six new paintings per artist) and asked to identify the artist based on what they learned a week prior. For the detailed and general recognition tests, participants were tested on the remaining half of the paintings that were studied during the training phase in Session 1.

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Session 1:

Training	Generalization	Detailed Recognition	General Recognition
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Session 2:

1-week delay	Generalization	Detailed Recognition	General Recognition
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Training	Generalization Test
<p>Painting: </p> <p>Location: </p> <p> <input type="button" value="Grossman"/> <input type="button" value="McNamara"/> <input type="button" value="Lindenberg"/> <input type="button" value="Grote"/> <input type="button" value="McKinley"/> <input type="button" value="Wexler"/> <input type="button" value="Hawkins"/> <input type="button" value="Juras"/> <input type="button" value="Schwartz"/> <input type="button" value="Petro"/> <input type="button" value="Walter"/> <input type="button" value="Schlorff"/> </p>	<p> </p> <p> <input type="button" value="Walter"/> <input type="button" value="Schwartz"/> <input type="button" value="Schlorff"/> <input type="button" value="McKinley"/> <input type="button" value="Grote"/> <input type="button" value="Hawkins"/> <input type="button" value="Wexler"/> <input type="button" value="Grossman"/> <input type="button" value="Lindenberg"/> <input type="button" value="Petro"/> <input type="button" value="Juras"/> <input type="button" value="McNamara"/> </p>
Detailed Recognition Test	General Recognition Test
<p> </p> <p> </p>	<p> </p> <p> <input type="button" value="McNamara"/> <input type="button" value="Schwartz"/> <input type="button" value="Petro"/> <input type="button" value="Lindenberg"/> <input type="button" value="Wexler"/> <input type="button" value="Walter"/> <input type="button" value="Grote"/> <input type="button" value="McKinley"/> <input type="button" value="Grossman"/> <input type="button" value="Juras"/> <input type="button" value="Schlorff"/> <input type="button" value="Hawkins"/> </p>

Figure 1. Schematic of experiment procedure and trials from each experiment phase. In Session 1, participants completed a training phase, followed by 3 different tests of knowledge specificity. Participants returned 1-week later (Session 2) to complete 3 delayed tests of knowledge specificity. In the training phase, participants were shown a painting and its corresponding landmark location along with 12 artist name options (top left). After selecting the artist name, participants were shown the correct artist of the painting before moving on to the next trial (not shown). In the generalization test (top right), participants were shown a novel (unstudied) painting and had to select the correct artist from 12 artist name options. In the detailed recognition test (bottom left), participants had to select the location of a previously studied painting. In the general recognition test (bottom right), participants were shown a previously studied landmark and had to identify the artist whose work was at that location.

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Figure 2. Procedure and schedules used during training. The procedure was counterbalanced between subjects such that some participants started with a blocked sequence and others started with an interleaved sequence. In the blocked sequence (B), all paintings of the same artist were presented in a random order. In the interleaved sequence (I), one painting from each of the interleaved artists was presented in a random order.

Analyses. A 2 (schedule: blocked vs. interleaved) $\times$ 2 (session: immediate vs. delayed)

within-subjects ANOVA was conducted for each test (generalization, detailed

recognition, and general recognition) to assess how training with different schedules

impacted generalized knowledge and specificity across sessions. Participants who

showed chance-levels of overall learning performance (regardless of schedule) on any

immediate test were excluded from the analysis of that particular test, as we are unable to adequately assess retention of knowledge on Session 2 in cases of no initial learning. For each test phase, we used a binomial probability distribution to determine chance-levels of performance using the number of trials in that test phase and cumulative probability of success from guessing on every trial. After applying these exclusion criteria to our 50 participants, we were left with 44 data points in the generalization test (accuracy ≥ 0.153), 19 in the detailed recognition test (accuracy ≥ 0.277), and 37 in the general recognition test (accuracy ≥ 0.166).

Results

Detailed recognition test. Average performance for each condition of the detailed recognition test is presented in Figure 3 (right, “Detailed Recognition”). A 2 (schedule) $\times$ 2 (session) within-subjects ANOVA revealed a main effect of schedule— blocked training led to better performance ($M = .29$, $SD = .10$) relative to interleaved training ($M = .23$, $SD = .08$) on this test of item-level specificity, $F(1, 18) = 8.34$, $MSE = 0.014$, $p = .01$, $\eta_p^2 = .32$. There was also a main effect of session—participants performed better on Session 1 ($M = .34$, $SD = .10$) relative to Session 2 ($M = .19$, $SD = .09$), $F(1, 18) = 55.87$, $MSE = 0.014$, $p < .001$, $\eta_p^2 = .76$. Performance in Session 2 was no greater than chance for neither the blocked ($M = .19$, $SD = .09$) nor interleaved ($M = .18$, $SD = .09$)

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condition, suggesting that no detailed information was retained after a 1-week delay.

The interaction between schedule and session was not significant, $F(1, 18) = 2.69$, $MSE = 0.014$, $p = .118$, $\eta_p^2 = .13$.

General recognition test. Average performance for each condition on the general recognition test is presented in Figure 3 (middle, “General Recognition”). A 2 (schedule) $\times$ 2 (session) within-subjects ANOVA revealed a main effect of schedule—accuracy was higher when participants had to remember artists associated with a given landmark for interleaved artists ($M = .32$, $SD = .16$) relative to blocked artists ($M = .15$, $SD = .09$). There was also a main effect of session—performance was higher in Session 1 ($M = .31$, $SD = .14$) relative to Session 2 ($M = .16$, $SD = .11$). There was also a schedule $\times$ session interaction, $F(1, 36) = 22.32$, $MSE = .014$, $p < .001$, $\eta_p^2 = .38$ —there was a large performance benefit of interleaved training ($M = .44$, $SD = .19$) relative to blocked training ($M = .18$, $SD = .10$) on Session 1 ($t(36) = 7.12$, $p < .001$, $d = 1.17$), but the interleaving benefit decreased significantly in Session 2 ($t(36) = 7.12$, $p < .001$, $d = .50$). The attenuation of the interleaving benefit was due to the fact that the interleaved condition suffered greater performance declines from Session 1 ($M = .44$, $SD = .19$) to Session 2 ($M = .20$, $SD = .13$, $t(36) = 6.91$, $p < .001$, $d = 1.14$), whereas the magnitude of performance declines from Session 1 ($M = .18$, $SD = .10$) to Session 2 ($M = .13$, $SD = .09$) was much smaller in the blocked group, $t(36) = 2.70$, $p = .011$, $d = .44$.

Generalization test. Average generalization performance for each condition is presented in Figure 3 (left, “Generalization”). A 2 (schedule) $\times$ 2 (session) within-subjects ANOVA revealed a main effect of schedule such that accuracy was higher for identifying novel paintings of interleaved artists ($M = .43$, $SD = .18$) relative to blocked artists ($M = .32$, $SD = .12$). There was also a main effect of session such that generalization accuracy showed improvements in Session 2 ($M = .39$, $SD = .15$) relative to Session 1 ($M = .36$, $SD = .15$). Notably, there was a schedule $\times$ session interaction, $F(1, 43) = 19.74$, $MSE = .004$, $p < .001$, $\eta_p^2 = .32$ —interleaved training led to superior generalization accuracy ($M = .43$, $SD = .18$) relative to blocked training on an immediate test ($M = .28$, $SD = .12$), $t(43) = 6.28$, $p < .001$. However, the interleaving benefit was attenuated after a delay, as the blocked condition showed significant improvements in performance on Session 2 ($M = .35$, $SD = .13$) relative to Session 1 ($M = .43$, $SD = .18$), $t(43) = 3.21$, $p = .003$, whereas the interleaved condition showed no significant difference in performance from Session 1 ($M = .43$, $SD = .18$) to Session 2 ($M = .42$, $SD = .18$), $t(43) = 1.03$, $p = .307$. The overall improvement in the blocked group may be due to the fact that feedback was provided during the generalization test, thereby giving the blocked group an opportunity to gain additional training at an interleaved study schedule and improve over the course of the generalization test. Similarly, Kornell and Bjork 2008 found that when participants received feedback during their test of category induction (generalization), the blocked group showed improvements across the 4 test blocks.

In an effort to minimize the influence of feedback and more accurately examine retention of general knowledge, we conducted another 2 (schedule) $\times$ 2 (session)

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within-subjects ANOVA on the generalization test, but restricted our analysis to the last 12 test trials from Session 1 and the first 12 test trials of Session 2. This restricted analysis revealed 2 main effects: interleaved training ($M = .42$, $SD = .26$) was still superior to blocked training ($M = .31$, $SD = .19$, $F(1, 43) = 11.16$, $MSE = 0.041$, $p = .002$, $\eta_p^2 = .21$), but the main effect of session revealed that performance does not in fact improve across a delay. We instead observe a significant decrease in general knowledge when comparing performance at the end of Session 1 ($M = .40$, $SD = .23$) relative to the beginning of Session 2 ($M = .32$, $SD = .21$), $F(1, 43) = 10.39$, $MSE = 0.041$, $p = .002$, $\eta_p^2 = .20$.

The blocking improvement seen in the schedule $\times$ session interaction suggests that the feedback provided during the generalization test phase had a significant role in improving generalization performance, particularly in the blocked condition. This is problematic in interpreting our results, as the additional learning from integrating feedback during the generalization test may have influenced performance on the subsequent tests that came after it (detailed and general recognition). Thus, in Experiment 2, we removed feedback from the generalization test to better examine (i.e., without the influence of feedback) the retention of general vs. detailed knowledge as a function of training with different study schedules.

Figure 3. Results of the generalization (left), general recognition (middle), and detailed recognition (right) tests in Experiment 1. Bars indicate group means, and dots indicate individual participant datapoints. Error bars indicate 95% confidence intervals of the mean.

Experiment 2: Re-examination of Sequencing Effects in the Absence of Feedback

Experiment 2 addressed a potential confound in our initial examination of optimal training schedules for general and detailed knowledge. The generalization test in Experiment 1 provided feedback which was determined to show improved performance in the blocked condition across test blocks (consistent with Kornell & Bjork 2008). This made the interpretation of subsequent tests (detailed and general recognition) difficult, as we were essentially providing additional learning opportunities during the generalization test. To address this issue, we removed feedback during the generalization test and repeated our initial experiment.

Method

Participants. Participants were recruited from the University of Texas at Austin's Psychology undergraduate subject pool. Participants received course credit for their

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participation in the study. There were 51 participants in Experiment 2 (age = 18-22, $M \pm SD = 18.94 \pm 1.10$, 10 Male), which was collected over the course of one academic year. The sample size was selected to match that of Experiment 1.

Materials and procedure. The materials and procedures in this experiment were nearly identical to those in Experiment 1. Experiment 2 differed from Experiment 1 solely in that no feedback was provided during either session of the generalization test.

Analyses. A 2 (schedule) $\times$ 2 (session) within-subjects ANOVA was conducted for each test (generalization, detailed recognition, and general recognition) to assess the effects of training with the different schedules across sessions on generalized knowledge and specificity. Participants who showed chance-levels of overall learning performance (regardless of schedule) on any immediate test were excluded from the analysis of that particular test, as we are unable to adequately assess retention of knowledge on Session 2 in cases of no initial learning. For each test phase, we used a binomial probability distribution to determine chance-levels of performance using the number of trials in that test phase and cumulative probability of success from guessing on every trial. After applying these exclusion criteria to our 51 participants, we were left with 44

data points in the generalization test (accuracy ≥ 0.153), 21 in the detailed recognition test (accuracy ≥ 0.277), and 40 in the general recognition test (accuracy ≥ 0.166).

Results

Detailed recognition test. Average performance for each condition of the detailed recognition test is presented in Figure 4 (right, “Detailed Recognition”). A 2 (schedule) $\times$ 2 (session) within-subjects ANOVA again revealed a main effect of schedule — blocked training led to better performance ($M = .32$, $SD = .13$) relative to interleaved training ($M = .25$, $SD = .10$) on the detailed recognition test, $F(1, 20) = 9.51$, $MSE = 0.018$, $p = .006$, $\eta_p^2 = .32$. There was also a main effect of session—participants performed better on Session 1 ($M = .36$, $SD = .13$) relative to Session 2 ($M = .21$, $SD = .10$), $F(1, 20) = 46.51$, $MSE = 0.018$, $p < .001$, $\eta_p^2 = .70$. Performance in Session 2 was no greater than chance for neither the blocked ($M = .23$, $SD = .11$) nor interleaved ($M = .20$, $SD = .08$) condition, suggesting that no detailed information was retained after a 1-week delay. The interaction between schedule and session was not significant, $F(1, 20) = 1.75$, $MSE = 0.018$, $p = .201$, $\eta_p^2 = .08$.

General recognition test. Average performance for each condition on the general recognition test is presented in Figure 4 (middle, “General Recognition”). A 2 (schedule) $\times$ 2 (session) within-subjects ANOVA revealed a main effect of schedule—accuracy was higher for the interleaved condition ($M = .34$, $SD = .14$) relative to the blocked condition ($M = .15$, $SD = .10$). There was also a main effect of session—performance

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was higher in Session 1 ($M = .33$, $SD = .14$) relative to Session 2 ($M = .16$, $SD = .10$).

There was also a schedule $\times$ session interaction, $F(1, 39) = 17.38$, $MSE = .016$, p

$< .001$, $\eta_p^2 = .31$ — there was initially a large performance benefit of interleaved training ($M = .47$, $SD = .16$) relative to blocked training ($M = .19$, $SD = .12$) on Session 1 ($t(39) = 9.10$, $p < .001$, $d = 1.44$), but this interleaving benefit was attenuated in Session 2 ($t(39) = 8.77$, $p < .001$, $d = .83$), as the interleaved condition suffered greater performance declines from Session 1 to Session 2 (*mean difference* = .25, $SD = .18$, $t(39) = 8.77$, $p < .001$, $d = 1.39$) relative to the blocked condition (*mean difference* = .08, $SD = .13$, $t(39) = 3.97$, $p < .001$, $d = .63$).

Generalization test. Average generalization performance for each condition is presented in Figure 4 (left, “Generalization”). A 2 (schedule) $\times$ 2 (session) within-subjects ANOVA revealed two main effects. There was a main effect of schedule such that accuracy was higher for identifying novel paintings of interleaved artists ($M = .40$, $SD = .15$) relative to blocked artists ($M = .32$, $SD = .13$), $F(1, 43) = 48.80$, $MSE = .005$, $p < .001$, $\eta_p^2 = .53$. There was also a main effect of session such that generalization accuracy was higher in Session 1 ($M = .33$, $SD = .14$) relative to Session 2 ($M = .29$, $SD = .15$), $F(1, 43) = 17.45$, $MSE = .005$, $p < .001$, $\eta_p^2 = .29$. There was no schedule $\times$ session interaction, $F(1, 43) = 1.81$, $MSE = .005$, $p < .001$, $\eta_p^2 = .04$.

Figure 4. Results of the generalization (left), general recognition (middle), and detailed recognition (right) tests in Experiment 2. Bars indicate group means, and dots indicate individual participant datapoints. Error bars indicate 95% confidence intervals of the mean.

Combined Analysis of Experiment 1 and Experiment 2. Experiment 1 differed from Experiment 2 in that feedback was provided during the generalization test. The general recognition and detailed recognition tests, however, were identical in design across Experiments 1 and 2 and had the same pattern of results. Thus, we repeated our ANOVA for the general recognition and detailed recognition tests by combining both data sets and adding “Experiment” as a between-subjects factor to determine if there were significant differences between results across the two experiments.

For the *detailed recognition test*, we found no significant difference in performance between the two experiments $F(1, 38) = 1.96$, $MSE = .012$, $p = .169$, $\eta_p^2 = .049$, nor were there any significant interactions that included the experiment (between-subjects) factor. The combined analysis across Experiments 1 and 2 reinforced the significant main effect of schedule (blocked > interleaved), $F(1, 38) = 17.32$, $MSE = .016$, $p < .001$, $\eta_p^2 = .31$ and significant main effect of session (session 1

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> session 2), $F(1, 38) = 100.36$, $MSE = .016$, $p < .001$, $\eta_p^2 = .73$. However, the combined analysis revealed a significant schedule $\times$ session interaction that was not present in the individual reporting of results in Experiment 1 or 2, $F(1, 38) = 4.28$, $MSE = .016$, $p < .045$, $\eta_p^2 = .10$. The interaction was driven by the fact that there was initially a statistically significant benefit of blocked training ($M = .40$, $SD = .13$) relative to interleaved training ($M = .30$, $SD = .10$) on the detailed recognition test in Session 1 ($t(39) = 3.70$, $p = .001$, $d = .58$), but the blocked and interleaved conditions did not differ significantly in performance on Session 2 (*mean difference* = .02, $SD = .13$, $t(39) = 1.15$, $p = .256$, $d = .182$), as both conditions showed performance levels that were no greater than chance.

For the *general recognition test*, we again found no significant difference in performance across the two experiments, $F(1, 75) = .313$, $MSE = .022$, $p = .577$, $\eta_p^2 = .004$, nor were there any significant interactions that included the experiment factor. The combined analysis across Experiments 1 and 2 reinforced the schedule $\times$ session interactions that were reported previously (in Experiments 1 and 2) for the general recognition test, $F(1, 75) = 39.33$, $MSE = .015$, $p < .001$, $\eta_p^2 = .34$.

Analysis of Implied Interactions Across Levels of Knowledge Specificity. Both Experiments 1 and 2 showed different patterns of results with respect to training sequences at various levels of knowledge specificity. Thus, we conducted a 3 (test type: generalization, general recognition, detailed recognition) $\times$ 2 (session) $\times$ 2 (schedule) within-subjects ANOVA to assess any potential interactions that included

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the test type variable. Participants were only included for this analysis if they passed the exclusion criteria for all three tests (above chance performance on immediate test for all 3 tests), which left 15 participants in Experiment 1 and 18 participants in Experiment 2. Scores within each test type (generalization, general recognition, and detailed recognition) were z-scored across sessions (session 1 and 2) to allow for more direct comparisons across the 3 tests. This analysis revealed a marginally significant 3-way interaction for test type $\times$ session $\times$ schedule in both Experiment 1, $F(2, 28) = 3.62$, $MSE = 2.09$ $p = .040$, $\eta_p^2 = .21$ and Experiment 2, $F(2, 34) = 5.07$, $MSE = 2.34$ $p = .012$, $\eta_p^2 = .23$. The 3-way interaction is further analyzed below.

Interaction between different learning sequences and knowledge specificity

In Experiment 1, the two-way test type $\times$ schedule interaction was found to be significant, $F(1, 14) = 14.84$, $MSE = 8.13$, $p < .001$, $\eta_p^2 = .52$, consistent with our pattern of results showing different tests benefit from different training schedules (Figure 3). Post-hoc tests restricted to 2 test types (generalization vs. general recognition, general recognition vs. detailed recognition, and generalization vs. detailed recognition) revealed that the test type $\times$ schedule interaction was significant for generalization vs. detailed recognition $F(1, 14) = 12.72$, $MSE = 7.31$, $p = .003$, $\eta_p^2 = .48$ and for general recognition vs. detailed recognition $F(1, 14) = 39.27$, $MSE = 15.55$, $p < .001$, $\eta_p^2 = .74$. This interaction is driven by the fact that detailed recognition benefitted from a blocked training schedule, whereas general recognition and generalization benefitted from an interleaved schedule. The test type $\times$ schedule interaction was not significant for

generalization vs. general recognition, as both tests showed an interleaving benefit, $F(1, 14) = 2.28, MSE = 1.53, p = .153, \eta_p^2 = .14$.

The two-way test type $\times$ schedule interaction in Experiment 2 was also found to be significant, $F(1, 17) = 20.84, MSE = 15.08, p < .001, \eta_p^2 = .55$, consistent with our results demonstrating the differential effects of training schedules on levels of knowledge (Figure 4). Post-hoc tests restricted to 2 test types (generalization vs. general recognition, general recognition vs. detailed recognition, and generalization vs. detailed recognition) revealed the same pattern of results as in Experiment 1: the test type $\times$ schedule interaction was significant for generalization vs. detailed recognition $F(1, 17) = 16.36, MSE = 18.22, p = .001, \eta_p^2 = .49$ and for general recognition vs. detailed recognition $F(1, 17) = 47.40, MSE = 26.29, p < .001, \eta_p^2 = .74$, but not for generalization vs. general recognition, $F(1, 17) = 1.47, MSE = .74, p = .242, \eta_p^2 = .08$. Overall, the significant test type $\times$ schedule interactions found across both Experiments 1 and 2 reveal that different levels of knowledge benefit from different training schedules.

Retention of various levels of knowledge

The two-way test type $\times$ session interaction was also significant in both Experiment 1, $F(1, 14) = 19.75, MSE = 8.27, p < .001, \eta_p^2 = .59$ and Experiment 2, $F(1, 17) = 10.08, MSE = 3.60, p < .001, \eta_p^2 = .37$. Post-hoc tests restricted to 2 test types (generalization vs. general recognition, general recognition vs. detailed recognition, and generalization vs. detailed recognition) revealed that the test type $\times$ session interaction was significant for generalization vs. general recognition in both Experiment 1, $F(1, 14)$

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= 21.59, $MSE = 6.29$, $p < .001$, $\eta_p^2 = .61$ and Experiment 2, $F(1, 17) = 11.26$, $MSE = 4.05$, $p = .004$, $\eta_p^2 = .40$. The differences in retention for generalization vs. general recognition is driven by the fact that general recognition suffers much greater performance declines over time relative to generalization performance, which is relatively stable. The test type $\times$ session interaction was also observed for generalization vs. detailed recognition in both Experiment 1, $F(1, 14) = 40.00$, $MSE = 16.21$, $p < .001$, $\eta_p^2 = .74$ and Experiment 2, $F(1, 17) = 16.72$, $MSE = 6.47$, $p = .001$, $\eta_p^2 = .50$. This interaction is driven by the fact that detailed recognition suffers large performance declines after a 1-week delay, whereas generalization performance is more stable. The test type $\times$ schedule interaction was not significant for general recognition vs. detailed recognition, as both tests show performance declines after one week in Experiment 1, $F(1, 14) = 4.12$, $MSE = 2.30$, $p = .062$, $\eta_p^2 = .23$ and Experiment 2, $F(1, 17) = .86$, $MSE = .28$, $p = .365$, $\eta_p^2 = .05$. Collectively, the test type $\times$ session interactions found across Experiments 1 and 2 suggest that while memory processes (general recognition and detailed recognition) show performance decrements after a delay, general knowledge (generalization/category induction) is much more stable.

Replicated Interaction Between Learning Sequences and Knowledge Specificity.

To address possible concerns related to the small sample sizes ($N=15$ in Experiment 1 and $N=18$ in Experiment 2) used in the previous analyses of implied interactions between learning sequence and knowledge specificity, we analyzed some data that was collected as part of another study to see if the test type $\times$ session

interaction could be replicated. The dataset was collected from a single session study that used six (instead of 12) artist categories that were all learned in a blocked OR interleaved sequence (between-subjects). In each condition, participants completed the same induction and source memory tests. The data analyzed contained 52 participants in the blocked condition, and 48 participants in the interleaved condition. Detailed methods can be found in the supplemental online materials. Critically, no performance-based exclusion criteria were applied to the data, as this version of the experiment did not have an appropriate way to assess overall performance regardless of learning condition (due to the learning sequence being between-subjects), nor did it have a retention component to assess.

We conducted a 3 (test type: generalization, general recognition, detailed recognition) $\times$ 2 (schedule) mixed ANOVA to see if we could replicate the test type $\times$ schedule interaction that was observed in Experiments 1 and 2. Even with this dataset, we replicated the test type $\times$ schedule interaction, $F(2, 196) = 18.075$, $MSE = 0.502$, $p < .001$, $\eta_p^2 = .16$. Post-hoc tests restricted to 2 test types (generalization vs. general recognition, general recognition vs. detailed recognition, and generalization vs. detailed recognition) revealed that the test type $\times$ schedule interaction was significant for generalization vs. detailed recognition $F(1, 98) = 37.79$, $MSE = .896$, $p < .001$, $\eta_p^2 = .27$ and for general recognition vs. detailed recognition $F(1, 98) = 18.72$, $MSE = .575$, $p < .001$, $\eta_p^2 = .16$. This interaction is driven by the fact that detailed recognition benefitted from a blocked training schedule, whereas general recognition and generalization benefitted from an interleaved schedule. The test type $\times$ schedule interaction was not significant for generalization vs. general recognition, as both tests

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showed an interleaving benefit, $F(1, 98) = 1.23$, $MSE = 0.035$, $p = .272$, $\eta_p^2 = .012$.

Thus, we were able to replicate the same pattern of results that we found in Experiments 1 and 2 with respect to the effects of sequencing on different levels of knowledge using an independent dataset even when learning sequence was manipulated between-subjects.

General Discussion

Across two experiments, we were able to determine the effects of different training sequences on the retention of general knowledge and detailed specificity when learning natural categories. Our study design is unique in that we were able to measure the acquisition of general and detailed knowledge within the same learning experience and examine which conditions are optimal for different types of knowledge retention. Overall, we found that blocked vs. interleaved training schedules differentially impact general vs. detailed knowledge. We found that interleaving is beneficial for improving general knowledge, as measured through our generalization and general recognition tests. However, results of our detailed recognition test revealed that blocking is beneficial for acquiring detailed memory and specificity. Additionally, we found differences in retention with respect to knowledge specificity: while general knowledge is largely retained even after a one-week delay, more detailed knowledge suffers greater losses over time.

Effect of Schedules on Levels of Knowledge Specificity

Our results demonstrate that different learning schedules are beneficial for different levels of knowledge specificity—interleaved training was beneficial for general category knowledge and even general recognition, but blocked training was beneficial

for highly detailed memory specificity. Prior work has suggested that interleaving category exemplars allows for discriminative contrast and allows learners to better differentiate between categories (Birnbaum et al., 2013; Carvalho & Goldstone, 2015; Kang & Pashler, 2012; Kornell & Bjork, 2008). With respect to our detailed recognition test, we found support for our prediction that blocking may operate in a similar manner in allowing for discriminative contrast at the *exemplar-level*. By presenting similar exemplars within the same category back-to-back, we may be enhancing one's ability to better discriminate the individual paintings within a category from one another. This enhanced discriminability at the exemplar-level may hinder the ability to extract general knowledge about a category, but enhance the ability to remember item-specific details. Future work should examine the boundaries of this blocking benefit for detailed memory specificity.

It is important to note the distinction between our study and the literature on the spacing effect in memory. The temporal spacing of items was held constant across conditions in our study. Our sequencing manipulation (blocked vs. interleaved) was applied at the *category-level*, and all items were presented in a *spaced*, rather than *massed* sequence at the *exemplar-level*. The spacing at the exemplar-level occurred when each exemplar was repeated 5 times within each blocked or interleaved sequence (Figure 2). Thus, each unique exemplar had the same temporal spacing in that it was equally spaced out in time across repetitions (which occurred roughly once every 6 exemplars), in both the blocked and interleaved conditions. In fact, the exemplar-level sequence only differed in that the adjacent exemplars were either from the same category (blocked condition), or from different categories (interleaved

condition). The consistent spacing at the exemplar-level makes our results all the more compelling as it demonstrates how comparisons between adjacent exemplars within a sequence (e.g., within- vs. between-category comparisons) can dramatically influence the type of knowledge gained from the individual items themselves. Future work could investigate how exemplar-level vs. category-level sequencing may influence knowledge acquisition and subsequent behavioral performance.

Retention of Generalized Knowledge vs. Specificity

Our results also revealed differences in the retention of general knowledge and memory specificity. We found that general knowledge appears to be more stable and is mostly retained over time, whereas more detailed memories are largely lost after a delay. The comparison of the generalization test to the general recognition test in Experiment 2 provides strong evidence for this theory (Figure 4). On immediate test, participants show similar performance levels in the generalization and general recognition test. In fact, general recognition performance was numerically higher than generalization in Session 1. However, after a 1-week delay, general recognition performance suffers sharp declines, whereas generalization performance shows minimal decrements.

Our findings with respect to knowledge retention provide support for *fuzzy trace theory* (Brainerd & Reyna, 1990, 1998), which claims that gist information is retained whereas verbatim information is lost over time. Our results also demonstrate a dissociation between generalization—making new inferences from previously learned material, and memory processes. These results suggest that the ability to generalize may rely on different cognitive mechanisms which allow for general knowledge to be

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more stable and flexibly used in new learning situations. Future studies could examine the neural mechanisms associated with acquiring and using general and vs. detailed knowledge to better assess this possibility.

One limitation in our study is the ability to more accurately assess possible interactions between the training schedules and knowledge retention. While it appears that the schedule that is immediately beneficial for learning retains its performance benefit over time, we found that the magnitude of the performance benefit drops in Session 2. One reason for the reduced benefit of any given schedule after a delay is due to the fact that performance levels drop across all conditions in Session 2, and performance in some conditions are at chance after a week delay, making it difficult to interpret our results with respect to sequencing effects on the retention of knowledge. For instance, we discussed in Experiment 1 that the schedule $\times$ session interaction observed in the general recognition test was likely driven by the fact that blocked performance is already low in Session 1 and drops to chance levels in Session 2, whereas interleaved performance starts out much higher and therefore still shows some knowledge retention in Session 2. Because the blocked condition reaches floor levels of performance in Session 2, we cannot assess the true magnitude of loss in general recognition for the blocked condition. Similarly, in the detailed recognition test, we are unable to assess whether the blocking benefit in Session 1 holds after a delay, as both conditions (blocked and interleaved) show chance levels of performance in Session 2. Thus, we are unable to determine whether blocked vs. interleaved training leads to different rates of forgetting, because performance in some conditions drop to chance levels after the delay. Future studies could consider using shorter retention

intervals and easier tests of memory that may allow for better assessment of learning that is successfully retained after a delay.

Conclusions

Our results demonstrate how different levels of knowledge specificity are optimally acquired and retained over time, and that different learning conditions can be optimal for improving specific outcomes. With respect to sequencing, it appears that an interleaved learning schedule improves one's general knowledge such as general recognition memory and general category knowledge, whereas a blocked learning schedule allows one to better discriminate fine item-level details. Furthermore, we found that while general knowledge is largely preserved over time, memory for details and even more general associative memory is mostly lost after a delay. These results illustrate the importance of leveraging the appropriate learning strategies that enhance performance and knowledge retention for specific tasks.

Author Contributions

S. M. Noh developed the study design for Experiment 1 and 2 together with A. R. Preston. R.A. Bjork helped develop the study design for Experiment 2. Testing, data collection, and data analysis were performed by S. M. Noh, and the data were interpreted under the supervision of A. R. Preston and R. A. Bjork. S. M. Noh drafted the manuscript, and A. R. Preston and R. A. Bjork provided critical revisions. All authors approved the final version of the manuscript for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Online Materials***Experiment details for independent dataset assessing the effects of sequencing on different levels of knowledge.*****Method**

Participants. Participants were recruited from the University of Texas at Austin's Psychology undergraduate subject pool. Participants received course credit for their participation in the study. There were 100 participants in the experiment (age = 18-35 years, $M \pm SD = 19.53 \pm 1.95$, 52 Male).

Materials. The images used for the experiments were 12 landscape paintings by each of 6 artists (Grossman, Hawkins, McNamara, Petro, Schlorff, and Wexler). Six unique paintings by each artist were used for the learning and memory test phases and six unique paintings were used for the generalization test. Paintings were cropped and resized to 500 x 333 pixels. In addition, we used images of 36 famous landmarks (18 natural and 18 manmade images cropped and resized to 333 x 333 pixels), each of which were paired with a unique painting during the learning phase. The landmark images also served as memory probes and choices during the source memory tests.

Procedure.

Learning Phase. During each learning trial, participants saw one of the paintings next to an image of a unique location at the top of the screen. Participants were told that their goal was to learn each artists' painting style, and that in a later phase, they would be

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shown a new painting and would have to identify the artist based on what they learned about each artists' style. To facilitate learning the artists' style, participants were asked to select the name of the artist to which each painting could be attributed from all six possibilities (presented as options at the bottom of the screen). Participants had up to 10 seconds to make their selection. After making their choice, the correct artist's name was presented as feedback (2 s) before moving on to the next painting-landmark pair. Importantly, across learning, the screen position associated with each artist's name was shuffled trial-to-trial to avoid spatial response biases during learning. During the learning phase, participants were exposed to six unique paintings for each of the six artists.

Each painting was paired with a unique landmark during learning. Participants were instructed that the landmarks corresponded to the nearest recognizable location where the painting could be found (e.g., a painting shown next to a picture of the Washington Monument indicated that the painting was located near that landmark). Participants were told to use the landmarks as an aid for learning but were not explicitly instructed that they would be tested on the associations between paintings and landmarks. Assignment of landmarks to individual paintings was determined randomly for each participant.

To assess the effects of different learning sequences on the acquisition of general (category) knowledge and detailed (source location) memory, we presented the six artist categories using one of two possible sequence types: blocked or interleaved. Roughly half of the participants (determined randomly) were assigned to each sequence type. For those in the blocked learning condition (N=52), all six paintings

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from one artist were presented sequentially, then shuffled and repeated a total of 5 times (30 trials), before moving on to paintings by the next artist. For those in the interleaved learning condition (N=48), one unique painting from each of six artists were presented sequentially, then shuffled and repeated a total of 5 times (30 trials), before moving on to the next unique painting from each of the same six artists.

Generalization Test

After the training phase, participants were tested on the general category-level knowledge they acquired during training. During the generalization test, participants were shown 36 new paintings (6 new paintings per artist) and asked to identify the correct artist based on what they learned about each artist's painting style during the training phase. Participants were shown a painting and had up to 15 seconds to select amongst the six artist name options. The 36 test trials were pseudo-randomly presented as six blocks of six paintings, with each block consisting of one painting from each artist presented in a random order.

Detailed Recognition Test

After the generalization test, participants were tested on their memory for specific details presented during the training phase. In the detailed recognition test, participants were asked to select the location that was paired with specific paintings that were studied in the training phase. Participants were shown a painting and asked to identify the location of the painting (i.e., the landmark that was paired with that painting during training). Participants were tested on half of the paintings they studied during the training phase (the other half was reserved for the general recognition test) without any feedback. For each of the 36 tested paintings, participants had 15 seconds

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to choose amongst 6 previously seen landmarks. The paintings for this phase were randomly selected (3 studied paintings per artist) and presented in a pseudo-random order across three blocks, with each block consisting of one painting from each artist presented in a random order. The response choices for each painting were landmarks that were paired with paintings by the same artist during training, so participants could not use general category-level information to eliminate any of the landmark options provided.

General Recognition Test

After the detailed recognition test, participants then completed a more general test of memory. The general recognition test differed from the detailed recognition test in that participants were asked to identify the artist associated with a given location from the training phase, without having to recall the specific details of the painting that was associated with that location. During the general recognition test, participants were shown a previously studied landmark and asked to remember the name of the artist whose painting was located at that landmark. Participants were tested on the 18 landmarks that did not overlap with the paintings that were tested in the previous phase. The 18 landmarks used were presented in a pseudo-random order, without feedback, across three blocks, with each block consisting of one painting from each artist presented in a random order. Participants were shown a picture of a landmark and had up to 15 seconds to select from six artist name options to make their choice.