Journal of Experimental Psychology: General
2011, Vol. 140, No. 4, 535–551

0096-3445/11/$12.00 DOI: 10.1037/a0024308

The Influence of Learning Methods on Collaboration: Prior Repeated Retrieval Enhances Retrieval Organization, Abolishes Collaborative Inhibition, and Promotes Post-Collaborative Memory

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Research on collaborative memory has unveiled the counterintuitive yet robust phenomenon that collaboration impairs group recall. A candidate explanation for this *collaborative inhibition* effect is the disruption of people's idiosyncratic retrieval strategies during collaboration, and it is hypothesized that employing methods that improve one's organization protects against retrieval disruption. Here it is investigated how one's learning method during the study phase—defined as either repeatedly studying or repeatedly retrieving information—influences retrieval organization and what effects this has on collaborative recall and post-collaborative individual recall. Results show that repeated retrieval consistently eliminated collaborative inhibition. This enabled participants to gain the most from re-exposure to materials recalled by their partners that they themselves did not recall and led to improvements in their individual memory following collaboration. This repeated retrieval advantage stemmed from the preferential manner in which this learning method strengthened retrieval organization. Findings are also discussed that reveal a relationship between retrieval organization and the interaction observed between learning method and short versus long delay seen in the testing effect literature. Finally, results show that the elusive benefits of cross-cuing during collaboration may be best detected with a longer study–test delay. Together, these findings illuminate when and how collaboration can enhance memory.

Keywords: collaborative remembering, retrieval organization, repeated study, repeated test, post-collaborative performance

Collaborative memory has received attention in a wide variety of disciplines over the years (see Bartlett, 1932; Clark & Stephenson, 1989; Durkheim, 1915; Halbwachs, 1950/1980; Hutchins, 1994; Jung, 1953; Rogoff & Mistry, 1985; Vygotsky, 1962, 1978; Wegner, 1987; Wundt, 1910/1916; see Barnier & Sutton, 2008; Hirst & Manier, 2008; Roediger, Zaromb, & Butler, 2009; Wertsch & Roediger, 2008, for reviews), but it has only recently been examined as a cognitive phenomenon with implications for both encoding and retrieval practices (see Weldon & Bellinger, 1997; Rajaram & Pereira-Pasarin, 2010). We specifically focused in the present research on *collaborative remembering*, defined as the recall output of a group of individuals working together to remember shared information or events (see Weldon & Bellinger, 1997). Our main goal was to examine how the (study) events happening prior to collaboration influence the mechanisms involved in collaborative remembering. By examining the nature of these antecedent events, we also wanted to assess how one's individual memory can be shaped by such collaboration.

In terms of study antecedents, we were interested in the critical role that learning methods could have on both collaborative recall and subsequent individual recall. We defined *learning methods* as the sequences of study and test trials in which the participants engage prior to working collaboratively, and following that individually, to recall the studied information. Specifically, participants could either engage in a method of *repeated study*, where they were exposed to the study material multiple times consecutively, or a method of *repeated retrieval*, where they attempted to recall the material multiple times consecutively (Roediger & Karpicke, 2006b). We also evaluated how these different learning methods affect the key cognitive mechanism of *retrieval organization* that could in turn affect the collaborative process. Retrieval organization refers to the method used by the participant to organize related information during recall, and it is a factor that is hypothesized to shape both individual and collaborative recall. Specific to the purposes of our study, we viewed retrieval organization as the clustering of items together from the same category during recall (Roenker, Thompson, & Brown, 1971). Finally, we examined the impact of a delay between one's learning method and collaboration to uncover potential differences the learning methods might exert across time on collaborative recall, post-collaborative individual recall, and retrieval organization. As such, this research brings together two rapidly emerging topics of inquiry, namely the testing effect (Roediger & Karpicke, 2006a) and collaborative memory (Rajaram & Pereira-Pasarin,

This article was published Online First July 11, 2011.
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2010) to answer questions that have major educational significance for individual learning and the popular practice of group study (Cohen, 1994; Johnson & Johnson, 2009; Kagan, 1990; Slavin, 1991).

Background to Collaborative Memory Research

In their seminal work on collaborative remembering, Weldon and Bellinger (1997) reported that contrary to intuition, collaborating in a group led to a decrease in recall performance. In line with previous research examining productivity, collaborative groups recalled more than individuals (Clark, Stephenson, & Kniveton, 1990; Lorge & Solomon, 1961). But more interestingly, the recall of collaborative groups was less than the recall of what are known as *nominal groups*, or groups in name only. These groups are formed by summing together the nonredundant responses of individuals who recalled by themselves, and such groups can be thought of as the "potential" recall of a group (see the Appendix for an example of how to calculate nominal group recall). Thus, collaborative groups did not perform up to their potential, leading to a phenomenon that Weldon and Bellinger called *collaborative inhibition*.

Collaborative Inhibition Is Attributed to Retrieval Disruption

A growing body of research shows that collaborative inhibition in recall is a robust phenomenon (see Rajaram & Pereira-Pasarin, 2010, for a review). Indeed, the reversal of this phenomenon, known as collaborative facilitation, where collaborative groups recall more than nominal groups, has rarely been demonstrated (see Meade, Nokes, & Morrow, 2009, for an exception). Interestingly, collaborative inhibition cannot be explained by appealing to simple motivational accounts, including that of social loafing (Weldon, Blair, & Heubsch, 2000; Collaros & Anderson, 1969; Diehl & Stroebe, 1987; see also Wright & Klumpp, 2004). The leading account of this phenomenon to date appears to be a cognitive one, where collaborative inhibition is hypothesized to arise from retrieval disruption that occurs during collaboration (B. H. Basden, Basden, Bryner, & Thomas, 1997). According to this account, each participant develops her own retrieval strategy of the study materials based on past experiences and knowledge and brings such an idiosyncratic strategy to the recall situation. Collaboration disrupts this idiosyncratic organization of the material, as each contributing participant listens to the recall output of others who likely bring a somewhat different strategy.

In line with this retrieval disruption argument, when study material can be organized in one specific fashion (e.g., organizing a small number of exemplars within each category compared with a large number), thereby increasing the probability that all group members have developed similar organization and are thus less likely to disrupt each other, collaborative inhibition attenuates or disappears (B. H. Basden et al., 1997). Similarly, collaborative inhibition also disappears when collaborative groups are forced to encode items in the same order (Finlay, Hitch, & Meudell, 2000). Such disruptions are hypothesized to be similar to *part-list cuing* in individual recall (D. R. Basden & Basden, 1995). The part-list cuing effect occurs when presenting participants with a subset of the studied material impairs their ability to recall the nonpresented material compared to a free recall task where no cues are presented (D. R. Basden & Basden, 1995; D. R. Basden, Basden, & Galloway, 1977; Roediger & Neely, 1982).

These above findings suggest that encoding operations that modulate the organization of studied material, and presumably the subsequent occurrence of retrieval disruption, should also change the size of collaborative inhibition. Thus, from a theoretical perspective it is important to examine the study antecedents to collaboration that can bring about changes in retrieval organization. From an applied perspective, learning methods that can result in the strengthening of retrieval organization and promote accurate recall in group or individual recall situations constitute some of the most relevant antecedents prior to collaboration. An understanding of what learning methods are most beneficial to later collaborations with others can be potentially applied to a variety of contexts. These contexts could include the most obvious educational implications for group activities to more diversified areas such as eyewitness testimony and political discussion groups.

The Importance of Study and Retrieval Repetitions in Shaping Retrieval Disruption and Collaborative Inhibition

In determining what learning methods would be the most pertinent to employ, we turned to the venerable literature on the effects of repetition on individual memory. Considerable evidence shows that repeated study improves memory (e.g., Braun & Rubin, 1998; Crowder, 1976; Greene, 1989). Classic work by Rundus (1971) has further shown that repetition of words promotes more rehearsals of those words, and increased rehearsals are associated with better organization of the words. Extrapolating these ideas to collaborative settings, B. H. Basden, Basden, and Henry (2000) demonstrated that repeated exposure to information, accomplished via three repeated study–test cycles, eliminated collaborative inhibition and improved retrieval organization across recall trials. Thus, study and/or test repetitions can be powerful ways to overcome collaborative inhibition in group recall. However, as this particular study interwove repeated study and repeated retrieval trials, it failed to isolate the separate influences that repeated study and repeated retrieval produce on collaborative recall or retrieval organization.

Pereira-Pasarin and Rajaram (2011) empirically assessed the selective influence of repeated study on collaborative recall and retrieval organization by introducing repetition only at study. Participants worked alone to study a list of categorized words, where half of the words were presented only once, whereas the remaining half were repeated three times in a spaced format throughout the list. Later, participants recalled the words either individually (where the recall of three individuals was combined to create nominal group recall) or as part of collaborative groups consisting of triads. The findings showed that repeated studying alone can improve retrieval organization and reduce collaborative inhibition. These findings also indicate that under certain conditions, such as repeated studying, collaborative inhibition in group recall can attenuate even if members bring differing strategies to the collaboration situation. Such attenuation occurs because multiple study opportunities allow participants to strengthen their respective retrieval organization of items. As a result of this strengthening of retrieval organization, participants are better able to maintain their own retrieval sequences during collaboration (Pereira-Pasarin & Rajaram, 2011).

Given Pereira-Pasarin and Rajaram's (2011) finding that repeated studying improved retrieval organization and protected individual recall *during* collaboration, one could predict that the resulting improvement in individual recall contributions during collaboration should lead to improved recall later when participants work by themselves. However, this possibility of post-collaborative improvements occurring as a result of repeated study remains unexplored. Instead, the broader question concerning the reciprocal benefits between collaborative and individual recall has been addressed under conditions that involved repeated retrieval. Specifically, Blumen and Rajaram (2008) developed a framework that predicted when collaborative recall would enhance subsequent individual recall, and proposed two opposing forces during collaboration that shape later individual recall: retrieval disruption, which has been discussed previously, and *re-exposure effects*. Re-exposure effects occur when participants are re-exposed to the study material during collaboration via the recall of their fellow group members. Thus, re-exposure essentially acts as a second "study" opportunity, and some research has reported that collaboration benefits subsequent individual recall presumably through such re-exposure (Stephenson & Wagner, 1989; Weldon & Bellinger, 1997; Yuker, 1955; but see Finlay et al., 2000).

Blumen and Rajaram (2008) found that final individual recall was significantly higher for participants who had either previously worked in collaborative groups twice (CCI) or who had first recalled by themselves before collaborating in a group (ICI) before the final individual recall, compared to those who did not collaborate earlier (III). But it remains to be determined whether a method of repeated retrieval promotes retrieval organization that both reduces collaborative inhibition and enhances post-collaborative individual recall. This question is also relevant in the context of some recent findings from related paradigms that show post-collaborative deficits, instead of gains, in individual memory as a function of prior collaboration (e.g., Brown, Coman, & Hirst, 2009; Coman, Manier, & Hirst, 2009). In brief, past research suggests that repeated study and repeated retrieval can be beneficial for collaborative and post-collaborative recalls, respectively, but the respective and relative efficacy of these learning methods on all three components of interest here, collaborative recall, retrieval organization, and post-collaborative individual recall, has not been investigated.

Balancing Retrieval Disruption and Re-Exposure Effects: The Role of the Testing Effect

A crucial point to emerge from past studies is that optimum benefits of group collaboration on recall may be achieved by balancing the two opposing forces that occur during collaboration: reducing retrieval disruption (as indexed by improved retrieval organization and reduced collaborative inhibition) and increasing re-exposure benefits (as indexed by increased post-collaborative recall). In the present study we systematically examined the relative roles of the two learning methods, repeated study and repeated retrieval, in achieving such outcomes. This aim brought our work into contact with a phenomenon of great interest in the present literature known as the *testing effect* (Roediger & Karpicke, 2006a; Tulving, 1967). This phenomenon refers to the highly robust finding of improved retention of information from taking a test (Roediger & Karpicke, 2006b). A striking aspect of this finding is that taking a test is a much more effective method for retention of learned information across time compared with restudying for an equivalent amount of time (or an equal number of times) as test taking (see Roediger & Karpicke, 2006a, for a review).

Thus, repeated study and repeated testing exert strikingly different effects on later individual recall as a function of study–test delay. For instance, Roediger and Karpicke (2006b, Experiment 2) compared participants who studied a passage four consecutive times (SSSS) with those who studied the passage once followed by three consecutive recall tests (STTT), where a final recall test occurred either after 5 min or 1 week. Repeated study produced higher recall when the final test occurred after a short delay, but in a reversal prior repeated testing produced higher recall at long delay (see also Hogan & Kintsch, 1971; Wheeler, Ewers, & Buonanno, 2003). The testing effect has since been demonstrated across a wide variety of situations and materials in individual memory performance. Our design provided an opportunity to examine its little known effects on collaborative and post-collaborative recalls while simultaneously taking into account its effects on retrieval organization that we describe next.

The Relationship Between Learning Methods, Recall, and Retrieval Organization

Critical to the novel questions addressed in the present study, the testing effect literature has recently revealed a link between strong organization in recall and the benefits of repeated testing (Zaromb & Roediger, 2010; see also Masson & McDaniel, 1981). Specifically, Zaromb and Roediger (2010) recently reported the standard testing effect using free recall measures, where repeated studying (eight study opportunities) of categorized lists led to lower recall than repeated testing (four study opportunities and four opportunities of taking a test) on final recall after a 2-day delay (Experiment 1). Critically, this pattern was accompanied by higher organization of recalled exemplars in the repeated testing condition. Similarly, two study opportunities produced lower recall and less retrieval organization of materials than a case where participants had one study opportunity followed by one testing opportunity on a final recall test that took place 1 day later (Experiment 2). Thus, one key reason for the long-term benefits of repeated testing is that this learning method promotes better retrieval organization that endures across time.

In the present study, our design allowed us to test the roles of repeated study and repeated retrieval on recall and retrieval organization under conditions that not only included a delayed recall condition (Zaromb & Roediger, 2010) but additionally provided a comparison between a short delay (7 min) and a longer delay (2 hr) between the learning phase and the final recall test. We chose the longer delay of 2 hr, which was intentionally less than the typical delays of 1–7 days used in individual recall designs, because our study conditions used fewer study and study–test opportunities during the learning phase than past research on the testing effect. As such, these experimental parameters provide useful generalizations of the key findings related to repeated testing, retrieval organization, and level of recall. We provide further information in the Method section on the selection of study–test delays used in the present study.

The inclusion of both short and long delays not only enabled a replication of short-term benefits of repeated study and long-term benefits of repeated retrieval in individual recall, it also allowed us to examine the patterns of retrieval organization across the two learning methods at these two delays, especially as these patterns might subsequently influence collaborative and post-collaborative recalls. In this context, Rundus's (1971) classic work noted earlier showed that repeated study promotes rehearsal and thereby increases retrieval organization, as would be the case in the present repeated study condition. This process may be further enhanced with repeated retrieval, because the very act of recalling items ensures explicit rehearsal. Thus, both repeated study and repeated retrieval methods may promote organization of study materials by virtue of rehearsal, but repeatedly retrieving material might do so to a greater extent, as individuals are forced to think about the relationships among the various study items in order to recall them. As superior retrieval organization is expected to endure over time (Hunt & McDaniel, 1993; McDaniel, Moore, & Whiteman, 1998), the lower recall associated with repeated retrieval at short delay would sustain better across time as a result of superior organization.

Summary of Goals of Present Research

Prior research has demonstrated that collaborating groups recall significantly less than nominal groups, an outcome that is typically attributed to a disruption of people's idiosyncratic retrieval strategies during collaboration. It is hypothesized here that employing learning methods that improve one's organization of material would protect against retrieval disruption and that repeatedly retrieving information would be more effective in providing such protection than repeatedly studying information. In addition, repeated retrieval prior to collaboration would reduce retrieval disruption and enhance re-exposure effects such that these benefits would enhance individual recall at the post-collaborative stage. Thus, in this study we ask the following: Does a person's learning method, defined as either repeated study or repeated retrieval of the material, influence in different ways (a) collaborative recall (examined via the presence and size of collaborative inhibition), (b) post-collaborative individual recall of each collaborating member (examined via the dynamic between retrieval disruption and re-exposure effects during collaboration), and (c) retrieval organization in collaborative and individual recall?

As a related question, we also examined the impact of a delay between the learning method and retrieval on the collaborative process and post-collaborative individual memory. With respect to collaboration, the inclusion of delay is especially relevant because the extent to which a particular method improves organization can predict the durability of learning from that method. In this context, the manipulation of delay enabled a test of the elusive phenomenon of *cross-cuing*, the idea that the recollections of one individual can serve as cues to trigger recollections in another individual that would not otherwise have been recalled (Meudell, Hitch, & Kirby, 1992; Meudell, Hitch, & Boyle, 1995; Takahashi & Saito, 2004). Past attempts at detecting cross-cuing benefits might have failed (Meudell et al., 1992, Meudell et al., 1995), because when retrieval disruption is effective, it clouds the cross-cuing benefits that might be occurring, resulting in a net outcome of collaborative inhibition. But if retrieval disruption was reduced and collaborative inhibition was to be eliminated, then cross-cuing benefits could become evident. Consistent with this reasoning, Takahashi and Saito (2004) reported cross-cuing benefits at a 1-week study–test delay (as indexed by collaborative facilitation). They argued that cross-cuing benefits may always be present, but become useful only after a long delay. This finding is parallel to other reports that after a delay, part-set cues in individual recall act in a positive way by facilitating recall of the nonpresented items at test (Raaijmakers & Phaf, 1999). One reason why such reversals in the disruptive effects of cues (i.e., part-set cues in individual recall or partner responses during collaboration) might occur is that when participants have more to recall they are more likely to be disrupted (e.g., Roediger, 1978). However, when they have less to recall (as is typically the case after increased study–test delay), disruption is less harmful and others' responses may in fact begin to serve as recall cues (see also Pereira-Pasarin & Rajaram, 2011). A manipulation of delay here allows a test of whether the scant reports of cross-cuing benefits can be detected at long delay in our study, as evidenced by the disappearance of collaborative inhibition, and whether this in turn would produce a beneficial effect on post-collaborative recall.

Method

Participants and Design

This experiment consisted of a 2 (learning method: repeated study vs. repeated retrieval) $\times$ 2 (group recall: collaborative vs. nominal) $\times$ 2 (delay: short vs. long) between-subjects design. Due to the intricate nature of this study, the full design is represented in Table 1. The overall study was divided into two large segments: the *learning method* segment that consisted of three phases and the *memory measures* segment that consisted of the remaining two phases. The study also included a short (7-min) and a long (120-min) delay between these two segments. A total of 288 participants were tested, with 12 triads of participants assigned to each condition.

As the experimental design included both collaborative recall (Phase 4) and individual recall (Phase 5) at short and long delays, we used pilot work to determine the duration of the long delay and intentionally selected 2 hr in order to simultaneously guard against ceiling effects (in collaborative recall) and floor effects (e.g., in individual recall at long delays) in recall performance. This calibrated choice of delay proved successful, as the highest recall (.86) and the lowest recall (.41) across the conditions were away from ceiling and floor performances.

Materials

The stimuli consisted of 180 categorized words, with 15 categories and 12 exemplars per category. The words were taken from Van Overschelde, Rawson, and Dunlosky (2004). The words were equally divided into two study lists, which were buffered with four items from separate, nonused categories from Van Overschelde et al. (i.e., two buffers each at the beginning and end). This was done to manage the study list length while ensuring the use of a large sample of items. The two lists were used equally often across participants within each condition. The lists were balanced across two criteria: taxonomic frequency and word length. The lists did

Table 1
Experimental Design for the Four Conditions for Both Short and Long Delay Groups

	Repeated study		Repeated retrieval	
	Nominal	Collaborative	Nominal	Collaborative
Learning method				
Phase 1	Study	Study	Study	Study
Phase 2	Study	Study	I-Recall	I-Recall
Phase 3	Study	Study	I-Recall	I-Recall
	Delay—short delay (7 min) or long delay (120 min)			
Memory measures				
Phase 4 (Group Recall)	I (N)-Recall	C-Recall	I (N)-Recall	C-Recall
Phase 5 (Individual Recall)	I-Recall	I-Recall	I-Recall	I-Recall

Note. I-Recall = Individual Recall; I (N)-Recall = Nominal Group Recall; C-Recall = Collaborative Group Recall.

not significantly differ in terms of either taxonomic frequency ($t <$ 1) or word length ($t < 1$), and each list was pseudorandomized with the constraint that no two items from the same category appeared consecutively. Finally, two additional lists were created, by reversing the order of the first two lists. Any given participant saw six exemplars from each category. In each of the four lists, the order of the words was identical for all participants.

We purposely selected categorized words as study stimuli because they lend themselves to the calculation of retrieval organization, known as the adjusted ratio of clustering (ARC) scores (Roenker et al., 1971). As mentioned in the introduction, ARC scores represent the strength of retrieval organization in terms of category repetitions during recall and are calculated by quantifying in recall the degree to which participants cluster items from the same taxonomic category.

Procedure

After collecting informed consent, each participant was tested individually in the *learning method* segment of the experiment (in all three phases for both repeated study and repeated retrieval). The beginning of this sequence was identical for all conditions. Participants were seated in front of separate computers and presented the study list (Phase 1), where each item was presented for 6 s during each study phase (1 s of an asterisk, followed by 5 s for presentation of the exemplar itself). At the outset, the participants were told to study the material for a future unspecified memory test and were also asked to make pleasantness ratings for each word in order to enhance conceptual processing (Craik & Lockhart, 1972) and to protect against floor effects in the individual recall conditions at long delay. Participants were asked to rate the words according to their own judgment on a 5-point, Likert-type scale, with 1 being the least pleasant in meaning and 5 being the most pleasant.

After being presented with the study stimuli once, the procedure began to differ depending upon the condition. For participants in the Repeated Study-Nominal and Repeated Study-Collaborative conditions in both delay groups, they were immediately exposed to the same material in two more cycles (Phases 2 and 3), following the same procedure as noted above. For those participants in the Repeated Retrieval-Nominal and Repeated Retrieval-Collaborative conditions in both delay groups, they were given a recall protocol sheet and asked to write as many of the items they could recall in any order from the list of words presented to them on the computer (Phase 2). They were given a total of 7 min to recall. After completing this first recall protocol, the participants were given a second recall protocol and asked to go through the exact same procedure over the next 7 min (Phase 3).

After completing the *learning method* segment (i.e., the first three phases), participants across all conditions in both delay groups completed a spatial distracter task for 7 min to prevent additional processing of verbal information. Participants in the long delay group were then asked to return to the laboratory after approximately 120 min.

After the delay (short or long), the *memory measures* segment of the experiment began. Participants in the nominal conditions in both the delay groups (and across both Repeated Study-Nominal and Repeated Retrieval-Nominal conditions) once again worked individually. They were given a recall protocol sheet and asked to write as many of the items they could recall in any order from the list of words presented to them on the computer, exactly as during the *learning method* segment for the Repeated Retrieval conditions. For those participants in the collaborative conditions (Repeated Study-Collaborative and Repeated Retrieval-Collaborative) in both delay groups, this first phase of the *memory measures* segment was a collaborative trial (Phase 4). Three participants (all strangers) were brought together as a group (a triad).[1] They were asked to clearly say aloud their subject number (e.g., 503, 401) and a short sentence into a tape recorder that was used throughout the collaborative recall period. This enabled us to track the items produced by each particular member of the group during collaboration, which was useful for calculating additional measures (described later in the Results section).

[1] We ensured that all members of a triad were strangers, and we did not sporadically include individuals who knew one another. This was done because previous research has shown that friends or couples can often attenuate the collaborative inhibition effect (e.g., Andersson & Rönnberg, 1995, Andersson & Rönnberg, 1996; Johansson et al., 2000, Johansson et al., 2005; Ross, Spencer, Linardatos, Lam, & Perunovic, 2004).

The participants were then given a recall protocol sheet and asked to write as many of the items they could recall in any order from the list of words presented to them on the computer. One member of the triad acted as a scribe, writing down the collective answers of the group (see Blumen & Rajaram, 2009). Further, the members of the group could call out their responses as the words occurred to them and did not have to reach consensus about which items were actually studied. It was up to them to devise a method for solving disagreements, and it was emphasized that whatever method they chose to produce their recall was acceptable. The experimenter ensured that the recall sheet on which the scribe noted the recalled items remained in full view of all participants throughout the recall period. They were given 7 min to complete the recall task. The total time provided was sufficient for both individuals and groups to complete their recall task.

Next, all participants across all conditions were given another recall protocol sheet and asked to recall individually as much as they could of the study list items (I-Recall; Phase 5). There was no delay between Phase 4 and Phase 5. In all individual recall sessions (in the *learning method* as well as *memory measures* segments), participants worked separately and were not allowed to speak to one another.

Results

Several key dependent variables of interest were included in the analyses and each is defined the first time it is introduced. Figure 1 displays the mean and standard error values for recall in all the conditions of both the short and long delay groups for Phase 4 (group recall), while Figure 2 displays such values for Phase 5 (post-collaborative individual recall). Table 2 presents the mean and standard error values for the retrieval organization scores (ARC, for both Phase 4 and Phase 5) for all conditions. Additional figures are presented at various stages to highlight other key findings. The mean intrusions in recall across all conditions are reported in the Appendix. In brief, and in line with several studies that used a naturalistic or free-flowing collaborative procedure (Blumen & Rajaram, 2008, 2009; Finlay et al., 2000, Experiment 2 and 3; Johansson, Andersson, & Ronnberg, 2000, 2005; Pereira-Pasarin & Rajaram, 2011; Takahashi & Saito, 2004; Weldon & Bellinger, 1997; Yaron-Antar & Nachson, 2006), we also found that collaborative recall led to lower intrusions than did nominal group recall: Collaborative groups (M = 1.00) produced fewer intrusions than nominal groups (M = 3.26) in the Short Delay group, $F(1, 45) = 17.49$, $MSe = 3.43$, $p = .001$, and also in the Long Delay groups (collaborative groups, M = 0.71; nominal groups, M = 3.87), $F(1, 45) = 35.79$, $MSe = 3.28$, $p = .001$.

As the intrusion rates were significantly higher for nominal compared to collaborative groups, we used a conservative approach in reporting our results by conducting analyses on corrected recall data. That is, when both recall and intrusion rates are lower in the collaborative condition (as is usually the case with the free-flowing procedure), this correction ensures that collaborative

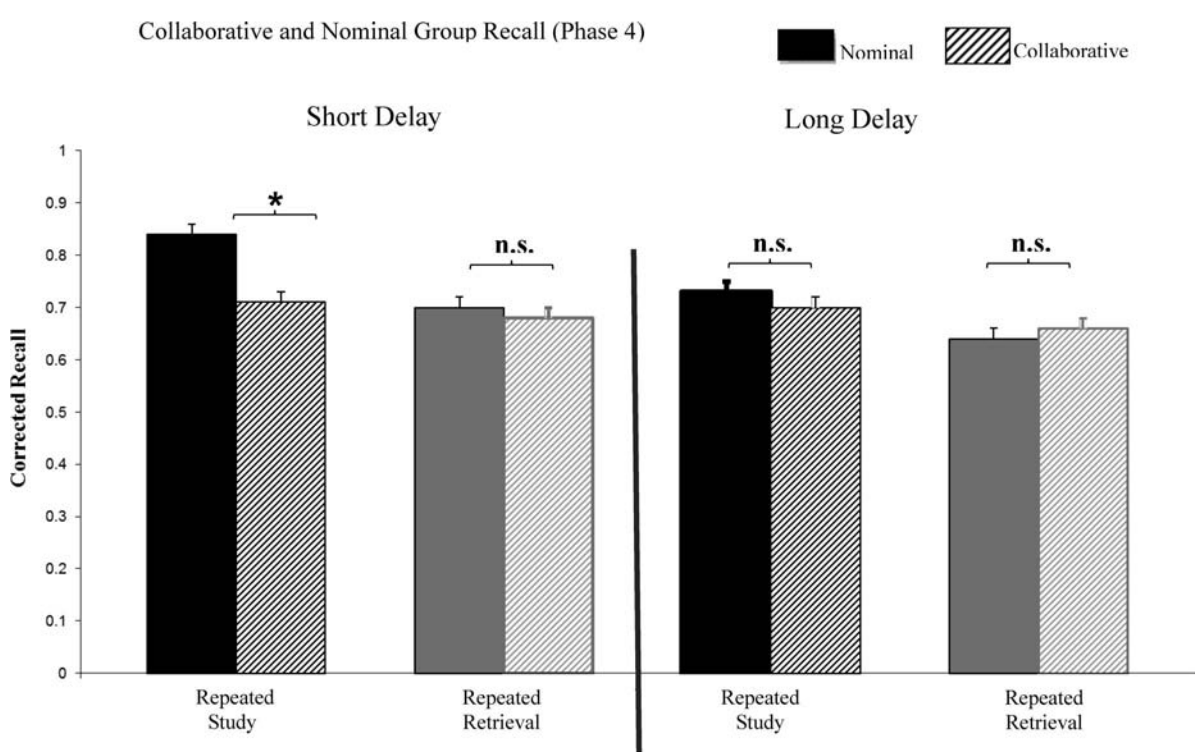

Figure 1. The left panel displays the mean and standard error values for the corrected nominal and collaborative group recall (Phase 4) at short delay, while the right panel displays these values at long delay. Asterisks indicate statistical significance between the two groups being compared. Error bars indicate standard error of the mean.

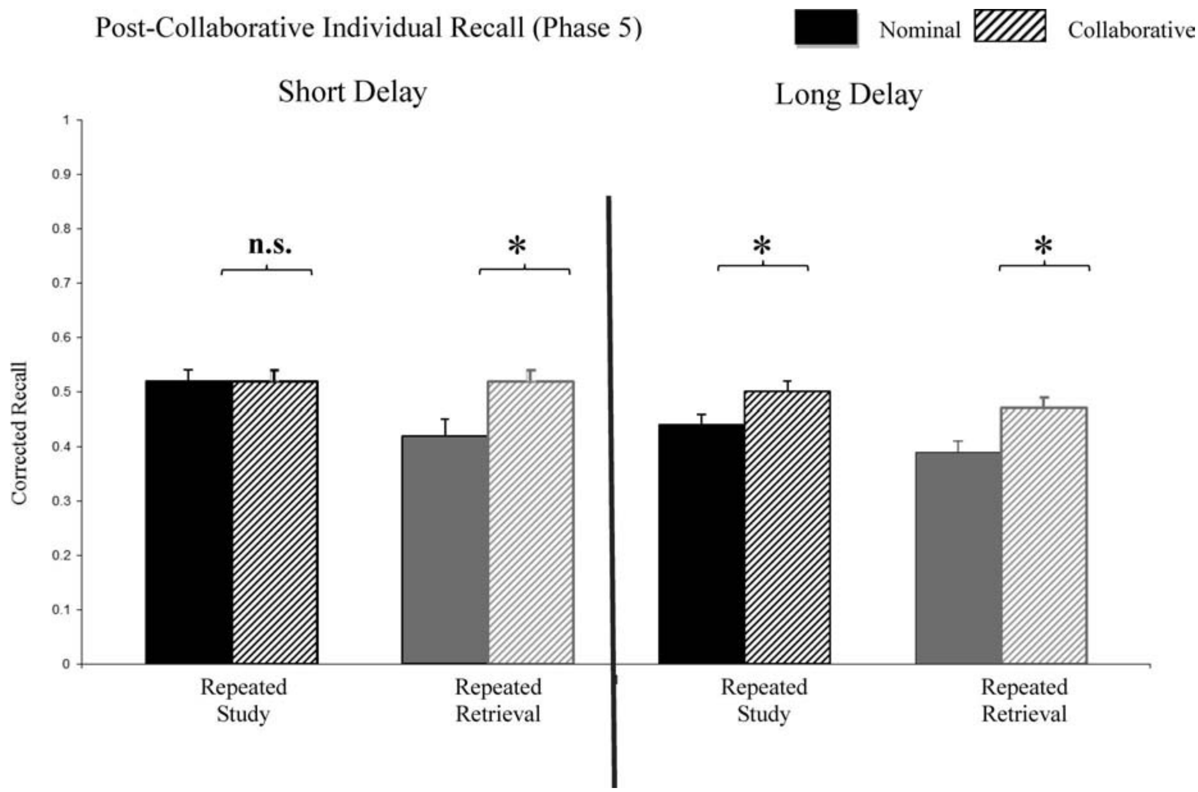

Figure 2. The left panel displays the mean and standard error values for corrected, post-collaborative individual recall (Phase 5) at short delay, while the right panel displays these values at long delay. Asterisks indicate statistical significance between the two groups being compared. Error bars indicate standard error of the mean.

inhibition reflects a robust reduction in accurate group recall over and above the general reduction in the responding rate. Therefore, across all analyses, the data from individual participants were scored in three separate ways. First, the total number of items correctly recalled was summed for each participant and the total number of intrusions was subtracted from it, providing what is referred to as "Corrected Individual Recall." Second, the nonredundant responses of three individuals, designated a priori as nominal group triads, but who recalled by themselves, were summed together and accordingly corrected, and this measure is referred to as "Corrected Nominal Group Recall." Finally, for those participants who collaborated in a group, the correct responses were summed together and accordingly corrected and are referred to as "Corrected Collaborative Group Recall." The corrected mean recall scores reported in the analyses are displayed in Figures 1 (Phase 4) and 2 (Phase 5). Further, to provide a full representation of the data, we also report the uncorrected mean recall scores (see the Appendix.) The alpha was set at $p < .05$ throughout unless noted otherwise. Finally, the inclusion of short and long delays allowed us to conduct comparisons across the delay periods, and those comparisons most pertinent to the key questions have been included where appropriate.

Table 2
Means (and Standard Errors) of Retrieval Organization (ARC) Scores Across the Four Conditions for Both Short and Long Delay Groups

	Short delay				Long delay			
	Repeated study		Repeated retrieval		Repeated study		Repeated retrieval	
Learning method	Nom	Coll	Nom	Coll	Nom	Coll	Nom	Coll
ARC scores								
Phase 4	.53 (.03)	.60 (.02)	.68 (.02)	.70 (.05)	.57 (.03)	.64 (.03)	.70 (.03)	.65 (.03)
Phase 5	.67 (.03)	.62 (.02)	.73 (.03)	.72 (.02)	.66 (.03)	.74 (.02)	.75 (.03)	.75 (.02)

Note. Nom = Nominal; Coll = Collaborative.

We first present the findings related to the effects of collaboration. We begin with Phase 4 concerning the collaborative-nominal comparisons in the form of group recall measures, and then present the post-collaborative recall consequences measured in Phase 5 in the form of individual recall measures. In the last section, we present the findings specific to individual recall (that come from the Nominal conditions) from Phase 4, as the implementation of the Repeated Study and Repeated Retrieval learning methods made it possible for us to evaluate the testing effect and its relation to retrieval organization.

Phase 4: Nominal Versus Collaborative Group Comparison

The central question of interest here is the impact of the learning method—in terms of repeated study versus repeated retrieval—on collaboration and group recall organization.

Collaborative inhibition at short delay. A 2 × 2 completely randomized (between subjects) analysis of variance (ANOVA) with group type (nominal vs. collaborative) and learning method (repeated study vs. repeated retrieval) as factors replicated two major prior findings (Short Delay, Phase 4; see Figure 1, left panel). One, nominal groups ($M = 0.77$) recalled significantly more than collaborative groups ($M = 0.69$), $F(1, 44) = 11.48$, $MSe = .01$, $p = .001$, replicating the collaborative inhibition effect (e.g., Weldon & Bellinger, 1997; B. H. Basden et al., 1997). Two, repeated study ($M = 0.77$) led to significantly greater group recall than did repeated retrieval ($M = 0.69$), $F(1, 44) = 12.76$, $MSe = .01$, $p = .001$, replicating the repeated study advantage in recall at short delays (e.g., Wheeler et al., 2003; Roediger & Karpicke, 2006b).

Critical to the novel predictions of this study, there was also a significant interaction between the learning method and group type in group recall, $F(1, 44) = 5.88$, $MSe = .01$, $p = .019$. Focused comparisons supported the predictions about the source of this interaction; collaborative inhibition was observed following repeated study but disappeared following repeated retrieval. Specifically, for the repeated study learning method, recall in the Repeated Study-Nominal condition ($M = 0.84$) was significantly higher than recall in the Repeated Study-Collaborative condition ($M = 0.71$), $t(22) = 4.50$, $SE = .03$, $p = .001$, $d = 1.84$. In contrast, the repeated retrieval conditions produced strikingly different patterns; group recall did not differ between the Repeated Retrieval-Nominal ($M = 0.70$) and Repeated Retrieval-Collaborative ($M = 0.68$) conditions, $t(22) = .63$, $SE = .03$, $p = .54$, $d = 0.26$, confirming the hypothesis that there would be low to nil collaborative inhibition following repeated retrieval during learning.[2] In sum, the central finding for group recall at short delay shows that the learning method differentially affects collaborative inhibition at short study–test delay (see Figure 1, left panel).

Collaborative inhibition at long delay. Interestingly and importantly, the collaborative inhibition effect changed across delay (see Figure 1, right panel, Long Delay, Phase 4 findings). A 2 × 2 completely randomized ANOVA showed that the comparison between overall nominal ($M = 0.69$) and collaborative ($M = 0.68$) group recalls was not significant, $F(1, 44) = .05$, $MSe = .01$, $p = .83$, demonstrating a rare circumstance in which the robust phenomenon of collaborative inhibition can be eliminated. With respect to the main effect of the learning method, although the short delay recall advantage for repeated study ($M = 0.72$) over repeated retrieval ($M = 0.65$) persisted at the 2-hr delay, $F(1, 44) = 6.29$, $MSe = .01$, $p = .02$ (see Figure 1), this outcome was not entirely surprising because this pattern occurred in group recall, whereas the long-term advantage known as the testing effect occurs in individual recall (as reported in a later section where the standard testing effect is replicated in individual recall). Furthermore, consistent with the testing effect literature, even group recall levels remained stable for the Repeated Retrieval-Nominal groups across the short ($M = 0.70$) and long ($M = 0.64$) delays, $t(22) = 1.36$, $SE = .04$, $p = .19$, $d = 0.56$, as well as for the Repeated Retrieval-Collaborative groups across the short ($M = 0.68$) and long ($M = 0.66$) delays, $t(22) = .75$, $SE = .03$, $p = .46$, $d = 0.31$, whereas these levels dropped significantly for the Repeated Study-Nominal groups across the short ($M = 0.84$) and long ($M = 0.73$) delays, $t(22) = 4.11$, $SE = .03$, $p = .001$, $d = 1.68$ (see Figure 1).

The interaction between the learning method and group type was not significant at the longer delay, $F(1, 44) = .75$, $MSe = .01$, $p = .39$. However, because this finding is of interest with respect to our a priori questions about the effects of delay on collaborative inhibition, focused comparisons were still conducted to confirm the absence of a collaborative inhibition effect in both the repeated study and repeated retrieval conditions following the long delay (see Figure 1, right panel). As with the short delay findings, repeated retrieval once again eliminated the collaborative inhibition effect such that group recall did not differ between Repeated Retrieval-Nominal ($M = 0.64$) and Repeated Retrieval-Collaborative ($M = 0.66$) conditions, $t(22) = -.45$, $SE = .04$, $p = .66$, $d = 0.18$. For the repeated study conditions, contrary to the short delay findings, the collaborative inhibition effect disappeared at long delay (see Takahashi & Saito, 2004), such that group recall between Repeated Study-Nominal ($M = 0.73$) and Repeated Study-Collaborative ($M = 0.70$) conditions no longer differed, $t(22) = .79$, $SE = .03$, $p = .44$, $d = 0.32$.[3]

[2] As mentioned at the beginning of the Results section, the results presented here are in terms of proportion corrected recall. When looking at uncorrected recall, there is a slight numerical advantage for the Repeated Retrieval-Nominal ($M = 0.74$) compared with Repeated Retrieval-Collaborative condition ($M = 0.69$), but this advantage is not statistically significant ($p = .11$). Because the intrusion rates between the nominal and collaborative groups were significantly different (and in favor of collaborative groups, as has been reported in prior studies as well), we took the conservative approach of conducting the analyses on the corrected recall values. However, as can be seen, even the uncorrected recall scores support our conclusions, despite the slight numerical advantage of Repeated Retrieval-Nominal.

[3] The uncorrected recall data here demonstrate a marginally significant collaborative inhibition effect, with Repeated Study-Nominal ($M = 0.77$) recalling more than Repeated Study-Collaborative ($M = 0.70$; $p = .06$). However, as we mentioned before, we choose the conservative approach of conducting analyses on the corrected recall data because the intrusion rates were significantly higher for nominal compared to collaborative groups (at both short and long delays). But even when looking at the uncorrected values, one can see that the overall numerical difference between Repeated Study-Nominal and Repeated Study-Collaborative conditions has decreased from 0.15 in the Short Delay condition to 0.07 in the Long Delay condition, $F(1, 44) = 5.53$, $MSe = .01$, $p = .03$, supporting the inference that the collaborative inhibition effect declined with delay in the repeated study condition and that it is a transient phenomenon.

Retrieval organization in group recall at short delay. As noted earlier, retrieval organization was measured with ARC scores. These scores were formed for nominal groups by averaging the scores for each individual, and were calculated for the collaborative groups, as in past research, on the basis of group output as a whole (rather than from the average of the output of individuals comprising the group).

A one-way between-subjects ANOVA confirmed that ARC scores (see Table 2 for the descriptive data) were significantly higher in Phase 4 for participants who used the learning method of repeated retrieval ($M = 0.69$) compared to participants who used repeated study ($M = 0.56$), $F(1, 42) = 13.70$, $MSe = .01$, $p = .001$. This ARC score advantage also manifested at more specific comparisons: In nominal group recall, a significant difference between Repeated Retrieval-Nominal ($M = 0.68$) and Repeated Study-Nominal ($M = 0.53$) was observed, $F(1, 18) = 11.58$, $MSe = .01$, $p = .003$, $d = 4.73$, and in collaborative group recall, a marginally significant difference between Repeated Retrieval-Collaborative ($M = 0.70$) and Repeated Study-Collaborative conditions ($M = 0.60$) was observed, $F(1, 22) = 4.04$, $MSe = .02$, $p = .06$, $d = 1.65$. Thus, as predicted, repeated retrieval preferentially enhanced retrieval organization in group recall.

Interestingly, collaboration itself did not disrupt retrieval organization, as the ARC scores did not differ in the Repeated Study conditions between Nominal (.53) and Collaborative (.60) group recall, $F(1, 23) = 3.26$, $MSe = .03$, $p = .09$, $d = 1.33$, or in the Repeated Retrieval conditions between Nominal ($M = 0.68$) and Collaborative ($M = 0.70$) group recall, $F(1, 18) = .165$, $MSe = .02$, $p = .69$, $d = 0.07$. Although this outcome may seem surprising at first in light of the argument that collaboration disrupts organization (B. H. Basden et al., 1997), it is in fact consistent with study conditions in previous research where repeated study or repeated retrieval occurs prior to collaboration, as was the case in the present design. Specifically, as we noted in the introduction, prior repetition conditions increase retrieval organization compared to single-study sessions (B. H. Basden et al., 1997, 2000; Pereira-Pasarin & Rajaram, 2011). Crucial for present purposes was the outcome that between the two learning methods, repeated retrieval was more effective than repeated study at enhancing retrieval organization during Phase 4, and this was true both generally and at specific collaborative versus nominal group recall comparisons. This differential superiority has implications for how these two learning methods might affect post-collaborative individual recall, a point to which we return later. Furthermore, as we also show later through a novel, category size analysis, the retrieval organization achieved through repeated study is more fragile and therefore likely more susceptible to disruption.

Retrieval organization in group recall at long delay. The ARC data at long delay paralleled those observed at short delay, such that the ARC scores were significantly higher in group recall following repeated retrieval ($M = 0.67$) compared with repeated study ($M = 0.60$), $F(1, 43) = 5.02$, $MSe = .06$, $p = .03$. Although this pattern suggests that the repeated study conditions once again should have yielded collaborative inhibition due to reduced ARC scores, it is also the case that unlike the findings at short delay, the ARC scores for collaborative group recall at long delay were comparable across repeated retrieval (.65) and repeated study (.64) conditions, $t(22) = -.21$, $SE = .06$, $p = .84$, $d = 0.09$. This pattern suggests that collaboration may become more productive for group recall as delay between study and test increases, and as such, collaborative inhibition begins to dissipate (consistent with this reasoning, the overall ARC scores in the repeated study conditions at long delay [.61] were numerically higher than at short delay [.56]), albeit this evidence is indirect. This implication is further supported by the cross-cuing findings we present in the next subsection.

With respect to the nominal and collaborative conditions, consistent with the short delay findings, the ARC scores did not differ either in the repeated study conditions between the nominal (.57) and collaborative (.64) group recalls, $t(22) = -1.26$, $SE = .05$, $p = .22$, $d = 0.51$, or in the repeated retrieval conditions between the nominal (.70) and the collaborative (.65) group recalls, $t(21) = 1.49$, $SE = .04$, $p = .15$, $d = 0.62$ (see Table 2, Phase 4 ARC data). In sum, with respect to the main finding of interest, the learning method of repeated retrieval continued to produce superior retrieval organization in group recall, even after a 2-hr delay.

Together, the Phase 4 (group recall) findings from the short and long delay manipulations reveal that the learning method of repeated retrieval preferentially protects collaborative recall from the negative effects of retrieval disruption.

Evidence for cross-cuing in collaborative recall. Turning our attention back to the collaborative recall data, the possible operation of cross-cuing was tested under the conditions where collaborative inhibition declined as a function of delay (in our design, the repeated study conditions). One way to detect cross-cuing is to see if situations exist in the data where recall levels are maintained over delay by the collaborating group but not by the nominal group. To assess this possibility, we examined the effects of study–test delay in the repeated study condition separately for the Collaborative and Nominal groups and found a significant decline in Nominal recall across delay, as indicated by the significant difference in recall between Short Delay, Repeated Study ($M = 0.84$) and Long Delay, Repeated Study ($M = 0.73$) conditions, $t(22) = 4.11$, $SE = .03$, $p = .001$, $d = 1.68$. In contrast, collaborative group recall remained stable with no significant difference in recall between Short Delay, Repeated Study ($M = 0.71$) and Long Delay, Repeated Study ($M = 0.70$) conditions, $t(22) = .11$, $SE = .04$, $p = .91$, $d = 0.04$.[4]

Phase 5: Post-Collaborative Individual Recall

Post-collaborative individual recall at short delay. In a 2 × 2 completely randomized (between subjects) ANOVA with group type (nominal vs. collaborative) and the learning method (repeated study vs. repeated retrieval) as factors, two interesting findings emerged at short delay (see Figure 2, left panel). First, as predicted, previous members of collaborative groups ($M = 0.52$) recalled significantly more than previous members of nominal

[4] As noted earlier (see Footnote 3), in the uncorrected recall measure, there was a reduction (but not a complete elimination) of the collaborative inhibition effect in the Repeated Study condition across delay. Important for the inferences about the cross-cuing effects, this reduction in the overall difference between nominal and collaborative groups stems from the loss of recall in Repeated Study-Nominal across the 2-hr delay (whereas the Repeated Study-Collaborative recall remained stable). Thus, the uncorrected recall data also support the conclusions about the effects of cross-cuing.

groups (M = 0.47), $F(1, 140) = 5.60$, MSe = .02, p = .02, replicating the re-exposure benefits of collaboration on post-collaborative individual recall (e.g., Blumen & Rajaram, 2008). Second, recall was significantly greater in the repeated study condition (M = 0.52) compared with the repeated retrieval condition (M = 0.47), $F(1, 140) = 6.12$, MSe = .02, p = .02, consistent with the repeated study advantage at short study–test delay in the testing effect paradigms (e.g., Wheeler et al., 2003; Roediger & Karpicke, 2006b).

Finally, and critical to the novel predictions of this study, there was also a significant interaction between the learning method and the group type, $F(1, 140) = 6.06$, MSe = .02, p = .02. Participants who repeatedly studied the material did not differ on post-collaborative individual recall across the Nominal (M = 0.52) and Collaborative (M = 0.52) groups, $t(70)$ = –.25, SE = .03, p = .80, d = 0.06. In contrast, participants who repeatedly retrieved the materials produced higher recall if they had earlier been in the Collaborative (M = 0.52) than in the Nominal (M = 0.42) condition, $t(70)$ = –3.12, SE = .03, p = .003, d = 0.74. Note that the recall levels were higher for the repeated study groups and this is because repeated study leads to higher recall at short study–test delays. But the benefits of collaboration per se were tied to whether or not collaborative inhibition occurred prior to post-collaborative recall (see Figure 1). Repeatedly retrieving material prior to collaboration abolished collaborative inhibition (Phase 4) and produced post-collaborative gains in individual recall (Phase 5), whereas repeated study prior to collaboration neither protected participants from collaborative inhibition (Phase 4) nor produced gains in post-collaborative individual recall (Phase 5).

In order to further assess this relationship between collaborative and post-collaborative recall, we examined what the participants had individually recalled during the collaborative session (i.e., Phase 4; accomplished via our tape-recordings of the sessions) and compared this recall with what the participants recalled individually during Phase 5. We sorted the participants' recall from Phase 4 to Phase 5 into four categories: (a) Loss = an item recalled by the participant during Phase 4 but which was forgotten (i.e., not recalled) during Phase 5; (b) Re-exposure Gain = an item recalled by one of the other collaborating partners during Phase 4 but recalled by the participant during Phase 5; (c) Recovery = an item not recalled by either of the collaborating partners or the participant during Phase 4 but recalled by the participant during Phase 5; and (d) Carry-Over = an item recalled by the participant during Phase 4 and recalled by the participant during Phase 5 (see Table 3 for descriptive data).

Consistent with the hypothesis that the benefits of collaboration were tied to whether or not collaborative inhibition occurred prior to post-collaborative recall, there were more "lost" items from Phase 4 to Phase 5 for the repeated study participants (Repeated Study-Collaborative, M = 3.85) than for repeated retrieval participants (Repeated Retrieval-Collaborative, M = 2.59), $t(58)$ = 2.32, SE = .54, p = .024, d = 0.60. Conversely, but consistent with this pattern, from Phase 4 to Phase 5 participants also "gained" (in terms of re-exposure benefits) numerically more items in the Repeated Retrieval-Collaborative condition (M = 27.63) than in the Repeated Study-Collaborative condition (M = 25.33), $t(58)$ = –1.41, SE = 1.63, p = .16, d = 0.36. There were also numerically more recoveries from Phase 4 to Phase 5 for Repeated Retrieval-Collaborative participants (M = 5.63) than for Repeated Study-Collaborative participants (M = 4.55), $t(58)$ = –1.54, SE = .70, p = .13, d = 0.40. This outcome is consistent with re-exposure gains in that a more secure organization (in the repeated retrieval condition) would also enable participants to recover more of their own items in later individual recall. Finally, there was no significant difference between repeated study (M = 17.64) and repeated retrieval (M = 18.74) in terms of carryovers from Phase 4 to Phase 5, $t(58)$ = –.48, SE = 2.29, p = .63, d = 0.12. In brief, the learning method of repeated retrieval promoted recovery and re-exposure benefits, whereas repeated study resulted in greater losses.

Post-collaborative individual recall at long delay. After a 2-hr delay, as predicted, individual recall of former members of collaborative groups (M = 0.49) was significantly higher than of those of former members of nominal groups (M = 0.42), $F(1, 140) = 11.34$, MSe = .02, p = .001. A comparison between repeated study (M = 0.47) and repeated retrieval (M = 0.43) was marginally significant, $F(1, 140) = 3.48$ MSe = .02, p = .06. The interaction between group type and the learning method was not significant, $F(1, 140)$ = .06, MSe = .02, p = .81.

This outcome shows that at long delay, both learning methods produced equivalent post-collaborative gains in individual recall, and this was confirmed in the follow-up comparisons. Specifically, for repeated study there was a significant advantage of having previously collaborated (M = 0.50) compared to not having collaborated (M = 0.44), $t(70)$ = –2.15, SE = .03, p = .04, d = 0.51, as well as for repeated retrieval (previously collaborated, M = 0.47; previously in the nominal group, (M = 0.39), $t(70)$ = –2.62, SE = .03, p = .01, d = 0.62.[5]

Retrieval organization in post-collaborative individual recall at short delay. At short delay, ARC analyses confirmed the prediction described in the Introduction that repeated retrieval improved recall organization (see Table 2, Phase 5). Specifically, a one-way ANOVA in Phase 5 showed that former collaborative group members in the Repeated Retrieval condition (M = 0.72) had significantly better organization than former collaborative group members in the Repeated Study condition (M = 0.62), $F(1, 70) = 8.64$, MSe = .02, p = .004, d = 0.69. A similar pattern was observed for individuals from the nominal groups in Phase 5, with higher ARC scores in the Repeated Retrieval (.73) than Repeated Study (.67) condition, although this difference did not reach sta-

Table 3
Means of Loss, Re-Exposure Gain, Recovery, and Carryover Scores for Repeated Study and Repeated Retrieval Groups

Learning method	Repeated study	Repeated retrieval
Loss	3.85	2.59
Re-exposure gain	25.33	27.63
Recovery	4.55	5.63
Carryover	17.64	18.74

[5] It should be noted that as both learning methods demonstrated post-collaborative gains after a long delay, it was not necessary to perform an analysis of gains, losses, recoveries, and re-exposure items as was done with the short delay group for the assessment of a relation between collaborative inhibition and post-collaborative recall.

tistical significance, $F(1, 66) = 2.13$, $MSe = .03$, $p = .15$, $d = 0.35$.

Retrieval organization in post-collaborative individual recall at long delay. After a 2-hr delay, the results showed a similar pattern (see Table 2, Phase 5); participants in the Repeated Retrieval-Nominal condition ($M = 0.75$) displayed superior organization to those in the Repeated Study-Nominal condition ($M = 0.66$), $t(69) = –2.34$, $SE = .04$, $p = .02$, $d = 0.56$. Interestingly, however, there was no longer a difference in the extent to which former members of collaborative groups organized material, as there was no difference between Repeated Study-Collaborative ($M = 0.74$) and Repeated Retrieval-Collaborative ($M = 0.75$), $t(68) = –.5$, $SE = .03$, $p = .62$, $d = 0.12$. This last finding is consistent with the equivalent ARC scores observed for these two groups (Repeated Study-Collaborative = .64; Repeated Retrieval-Collaborative = .65) earlier in Phase 4 group recall. In other words, after a 2-hr delay, collaboration became more useful in the Repeated Study condition and the collaborative organization developed during group recall cascaded down to post-collaborative individual recall as well.

Learning Method and the Testing Effect: The Role of Retrieval Organization in Individual Recall (Phase 4)

The questions tested here pertain to the first *individual recall* that occurred after the learning method segment (Phases 1–3) was completed. Before we turn to those data, for the sake of completion we report the mean recall values during Phases 2 and 3 for the individual data taken from the repeated retrieval nominal condition. At short delay, the mean recall values were .36 for Phase 2 and .39 for Phase 3, whereas at long delay, the mean recall values were .34 for Phase 2 and .38 for Phase 3. But as just noted, the individual recall scores were taken from the Nominal conditions in Phase 4 and served as the key units of analysis to provide a direct comparison to the standard testing effects. The individual recall data are summarized in Figure 3. In all cases, nominal group recall as the unit of analysis produced the same pattern of findings as the individual recall data. Therefore, for reasons of economy and in light of the focus on the individual recall performance in this section, we present the analyses here only for the individual recall data. (The nominal group recall data can be found in Figure 1.)

At short delay, the well-established repeated-study advantage (Roediger & Karpicke, 2006b; Wheeler et al., 2003) was replicated, such that individual recall was significantly higher following repeated study ($M = 0.50$) than repeated retrieval ($M = 0.42$) learning, $F(1, 70) = 9.69$, $MSe = .01$, $p = .003$, $d = 0.73$.

An increase in the study–test delay replicated another well-documented pattern observed in the testing effect literature in individual recall (see Roediger & Karpicke, 2006b). Even with a delay of only 2 hr (as opposed to the more traditional 1-week delay in the testing effect literature), individual recall following repeated study at short delay ($M = 0.50$) significantly declined at long delay ($M = 0.41$), $t(70) = 3.49$, $SE = .03$, $p = .001$, $d = 0.82$, but there was no such decline in recall for the learning method of repeated retrieval from short delay ($M = 0.42$) to long delay ($M = 0.38$), $t(70) = 1.25$, $SE = .03$, $p = .22$, $d = 0.29$.

The critical questions concerned whether the retrieval organization of individual recall would differ as a function of these different learning methods across different delays. Novel to our study we observed that at short delay significantly higher ARC scores were obtained in individual recall in the Repeated Retrieval condition ($M = 0.66$) compared with the Repeated Study condition ($M = 0.53$), $F(1, 66) = 11.60$, $MSe = .03$, $p = .001$, $d = 0.83$. A similar pattern was observed at long delay as well, such that a significantly higher ARC score was observed in individual recall in the Repeated Retrieval condition ($M = 0.71$) compared with the Repeated Study condition ($M = 0.57$), $t(21) = -4.26$, $SE = .03$, $p = .001$, $d = 1.78$. These latter patterns replicate the recent reports of significantly higher ARC scores following prior study–test rather than study-study opportunities on one-day delayed recall (Zaromb & Roediger, 2010, Experiment 2), and extend this finding in the present study to shorter delays (7 min versus 120 min).

Category size analysis. In conjunction with the ARC analysis that indexes organization by providing the total number of category repetitions that occur throughout a participant's recall protocol, we used a convergent measure of exemplar clustering in finer grained detail than is provided by ARC. We assessed whether the size of categories recalled might vary as a function of delay. This analysis is similar to assessing the recall of items within categories (Tulving & Pearlstone, 1966), but it allows us a unique

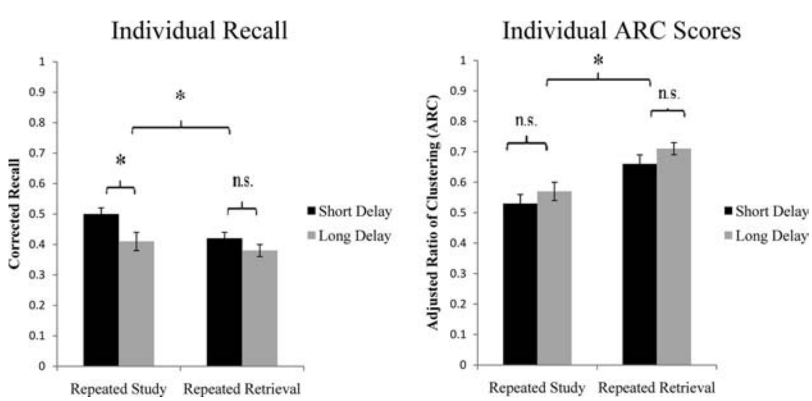

Figure 3. The testing effect in individual recall (Individual recall data come from Phase 4 Nominal Group Recall). Asterisks indicate statistical significance between the two groups being compared. Error bars indicate standard error of the mean.

index of the changes in categories as they unfold across time as a function of repeated study and repeated retrieval. Simply calculating items per category does not truly capture that aspect of exemplar fluctuations that we were interesting in analyzing. We conducted this convergent analysis because the size of category clusters in recall may be particularly important for understanding why one learning method (e.g., repeated study) may produce higher recall at short delay but reduced recall over time, whereas another learning method (e.g., repeated retrieval) may produce more stable recall over time. Specifically, if the retrieval organization induced by repeated study is not robust, then we expected that increased delay between study and test would reduce the number of exemplars recalled from a given category. Such a reduction is less likely to occur following the learning method of repeated retrieval if this learning method strengthens retrieval organization to a greater degree, as stronger organization is more likely to survive delay. In other words, a measure that is more sensitive to cluster size can help discern the relationship between learning method and retrieval organization, especially across time. The inclusion of two delays enabled a test of this novel question, and we refer to this as the "Category Size Analysis."

Each individual recall protocol (again from the Nominal conditions in Phase 4) was scored both for how many categories were recalled and for how many exemplars per category were recalled. The categories recalled were split into two groups: *small categories*, or the total number of categories where participants recalled two or fewer exemplars of the six possible ("two or fewer"), and *large categories*, or the total number of categories where participants recalled three or more exemplars of the six possible ("three or more"). A 2 $\times$ 2 completely randomized, between subjects ANOVA was conducted to determine if there were differences between the repeated study and repeated retrieval conditions in both short and long delay groups in terms of the number of categories that possessed "three or more" exemplars in Phase 4 (the "two or fewer" data produce a converse pattern and all of the means are displayed in Figure 4).

In examining the performance of individuals (i.e., individuals disentangled from their nominal groups), participants who repeatedly retrieved the material (M = 8.38) were less likely to recall larger numbers of exemplars per category ("three or more") on an immediate recall test than those who repeatedly studied the material (M = 9.67), $t(66)$ = 2.15, SE = .60, p = .04, d = 0.52. Critical for the present hypothesis, delay interacted with category size only in the repeated study condition. Whereas in the repeated study condition the number of categories recalled with three or more exemplars declined from short (M = 9.67) to long delay (M = 7.92), $t(70)$ = 2.69, SE = .65, p = .01, d = 0.63, there was no such decline observed for the repeated retrieval condition from short delay (M = 8.38) to long delay (M = 7.63), $t(65)$ = 1.06, SE = .70, p = .29, d = 0.26. This pattern was mirrored for the number of categories recalled with two or fewer exemplars, such that the recall of these categories increased with delay in the repeated study condition from short (M = 5.33) to long delay (M = 7.08), $t(70)$ = –2.69, SE = .65, p = .01, d = 0.63, but remained unchanged in the repeated retrieval condition from short (M = 6.63) to long delay (M = 7.37), $t(65)$ = –1.06, SE = .70, p = .29, d = 0.26. Together, this analysis showed that the learning method of repeated retrieval provided not only greater retrieval organization in terms of ARC (Zaromb & Roediger, 2010), but it also protected the recall of larger category clusters over time. The comparison between two delays for recall in our study afforded an opportunity to see that the repeated study learning method produced recall of more exemplars initially but a relatively more fragile organization such that delay reduced the presence of larger categories in recall. This tenuous nature of organization may explain why following repeated study, group members' collaborative recall nonetheless remains susceptible to disruption, even at short delay.

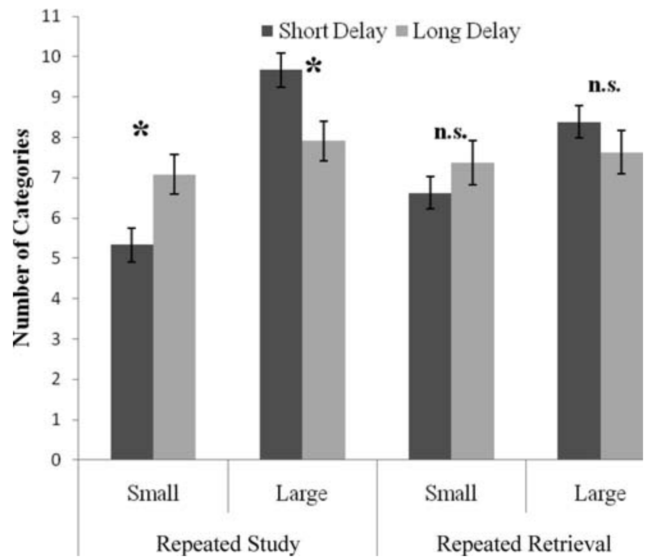

Figure 4. The category size analysis for changes in retrieval organization in the individual recall data in Phase 4 (derived from the nominal recall conditions) at short and long delays. Small = when two or fewer exemplars from a category were recalled; Large = when three or more exemplars from a category were recalled. Asterisks indicate statistical significance between the two groups being compared. Error bars indicate standard error of the mean.

General Discussion

It is common for people to experience new events as well as reminisce about past events with others. It is also a commonly held belief that such collaboration can enhance retrieval (Dixon, Gagnon, & Crow, 1998; Henkel & Rajaram, 2011). However, research has revealed the surprising phenomenon that people working together recall *less* together than their predicted potential. Such an outcome has important implications for understanding not only the cognitive theoretical bases of collaborative remembering but also the social and educational implications of collaboration. For instance, group learning is a popular method used by students to enhance learning and performance. As such, the conditions under which the costs of collaboration can be reduced and benefits enhanced are important to identify. Specifically within the cognitive realm, the phenomenon of collaborative inhibition is important to investigate both to understand the nature of group memory and also to determine how collaborative processes during group recall shape the post-collaborative memory of the participating members. The present study focused on these key issues. We discuss our findings in terms of the effects of antecedent learning methods on collaborative recall and on post-collaborative consequences and the effects of delay on these memory measures and on retrieval organization that affects both individual and group recall.

Effects of Learning Method on Collaboration, Post-Collaborative Recall, and Retrieval Organization

In this large-scale study, the short delay between the learning method and the memory measures segments paralleled the standard study–test delay used in studies of collaborative memory. Under these conditions, participants who engaged in a prior learning method of repeated study displayed the traditional collaborative inhibition effect (Weldon & Bellinger, 1997). These findings show that even though repeatedly studying material reduces collaborative inhibition in comparison to a single study opportunity (Pereira-Pasarin & Rajaram, 2011), it still cannot reliably eliminate collaborative inhibition. However, those who engaged in a prior method of repeated retrieval displayed no such collaborative inhibition, even at short delay. These findings also show for the first time the circumstances where benefits of repeated testing that are typically associated with long study–test delays in individual recall (e.g., Wheeler et al., 2003; Roediger & Karpicke, 2006b) can emerge even at short delay.

Our results demonstrated a rare instance when the robust phenomenon of collaborative inhibition can be eliminated. Retrieval organization can vary across participants, and this can be true even for categorical information, where differences could arise between the sequences in which participants recall categories and/or the sequences of exemplars recalled within such categories. But the act of taking multiple tests on the stimulus materials prior to collaboration allowed the individual participants to solidify their own idiosyncratic organization of the studied material such that recall was no longer susceptible to disruption despite the varying strategies that members presumably brought to the recall situation.

Blumen and Rajaram (2008) demonstrated similar results when they found that participants who had an opportunity to recall material individually prior to collaborating later had higher recall than those who had no such individual opportunity. Presumably, this is because the people who recalled the material by themselves first were able to secure retrieval organization, but Blumen and Rajaram's design did not allow for a definitive answer. In our study, this possibility was assessed with the ARC analysis, which demonstrated that repeated retrieval participants indeed had stronger retrieval organization than the repeated study participants. As a result of this stronger organization, the repeated retrieval participants were likely protected against the negative effects of retrieval disruption during collaboration, as suggested by the lack of collaborative inhibition.

With collaborative inhibition eliminated, repeated retrieval participants were then able to gain the most in terms of re-exposure benefits such that these participants had a clear recall advantage over repeated study participants, demonstrating a positive cascading benefit from Phase 4 to Phase 5 for those who had previously collaborated. This evidence for re-exposure benefits of collaboration receives support from the analysis of gains, losses, recoveries, and re-exposures, which assessed the downstream consequences of collaboration from Phase 4 to Phase 5 and showed that a prior history of repeated retrieval promoted recovery and re-exposure to material during collaboration.

Effects of Delay on Collaboration and Post-Collaborative Individual Recall

Interestingly and importantly, some of these results systematically changed across delay. After a delay of 2 hr between the *learning method* segment and the *memory measures* segment, neither participants in the repeated study nor the repeated retrieval condition displayed significant collaborative inhibition. A decline in collaborative inhibition in the repeated study condition after a 2-hr delay is consistent with earlier research noted in the Introduction that demonstrated that collaborative inhibition dissipates across a delay of 1 week (Takahashi & Saito, 2004). As the present study used a delay of only 2 hr, our findings provide converging evidence for the temporally constrained nature of the collaborative inhibition phenomenon that does not last across time.

These results also have implications for the possibility of cross-cuing. The dissipation of collaborative inhibition across time indicates that collaborative groups maintain their levels of recall over time because individuals within the groups provide cues (in the form of retrieved items) of use to other group members. Such cues are not available in individual recall, and this difference presumably contributes to a decline in recall over time for the nominal groups compared to collaborative groups. The present findings support the idea that such cues have to be occurring during collaboration; otherwise, their recall levels should have dropped in the same manner as their nominal counterparts' recall levels. As such, these outcomes are suggestive of the phenomenon of cross-cuing during collaboration at long delay.

Furthermore, after the 2-hr study–test delay, participants from the repeated study condition who had previously collaborated had the same recall advantage on their final individual recall (Phase 5) as the repeated retrieval participants. Thus, at longer study–test delays, there are indeed clear benefits to collaborating. This outcome indicates that when collaborative inhibition declined, participants using both learning methods were able to glean re-exposure benefits during collaboration. Taking together the findings from the short and long delay groups, the patterns show that post-collaborative gains in individual recall are associated with whether or not collaboration earlier produced decrements in group recall. That is, post-collaborative gains in Phase 5 were absent following collaborative inhibition in Phase 4 (short delay, repeated study condition) but present when no collaborative inhibition occurred earlier in Phase 4 (short delay, repeated retrieval condition; long delay both repeated study and repeated retrieval conditions). These findings clearly suggest that retrieval organization during the learning method segment and Phase 4, as well as retrieval disruption during collaboration, is associated with the extent to which collaboration produces later gains in individual recall.

Effects of Learning Method on Individual Recall and Retrieval Organization

The results from our nominal conditions led to an interesting intimation about the relationship between the testing effect and retrieval organization in recall. We replicated the interaction between learning method and delay on recall levels that has been well-documented in the testing effect literature (e.g., Hogan & Kintsch, 1971; Wheeler et al., 2003; Roediger & Karpicke, 2006b); repeatedly studying material produced an initial recall advantage compared with repeatedly retrieving material between learning method and retrieval, but this advantage declined significantly across delay. In contrast, repeatedly retrieving material produced stable recall across delay. Accompanying this interaction between learning method and delay were differences in the level of retrieval organization between the two learning methods; in line with the findings reported by Zaromb and Roediger (2010), we also found that at long delay the learning method of repeated retrieval produced higher retrieval organization (measured through the ARC scores) in recall than repeated study. In addition, our design also enabled a comparison at short delay, where despite higher recall in the repeated study condition, the retrieval organization was greater following repeated retrieval. The fact that the repeated retrieval method produces both stable recall across time and higher levels of retrieval organization points to a possible relationship between these two variables; when a learning method produces better organization, such learning holds up well across time.

The use of two different delays in our study also enabled us to investigate this modulation in recall in finer grained detail through our Category Size Analysis. This analysis examined the extent to which recall of a higher number of exemplars from a given category was sustained over time as a function of learning method. Repeated retrieval protected the recall of large categories across time, while repeated study did not. This novel finding further supports the idea that stronger retrieval organization in repeated retrieval produces stable recall across time (Hunt & McDaniel, 1993; McDaniel et al., 1988).

At first glance, one aspect of this finding may seem paradoxical in that repeated retrieval compared to repeated study improves organization, but at immediate test the history of repeated retrieval produces lower recall. However, this seeming paradox is resolved when the effects of study–test delay on recall are compared across short and long delays, and the patterns of retrieval organization are simultaneously taken into account. It is likely that participants engaged in less relational processing during repeated study compared to repeated retrieval. Further, we predicted in the Introduction that information that is found to be better organized (i.e., via relational processing) at short study–test delay will be more likely to endure across delay than information that is less well organized (i.e., encoded with less relational processing). The recall data upheld these predictions and thus supported the prediction that engaging in multiple test attempts helped to solidify one's idiosyncratic organization of the studied material via relational processing, which then protected one against the negative effects of retrieval disruption during collaboration. Further, as noted in the previous section on findings for post-collaborative recall, such protection allowed one to gain the most in terms of re-exposure effects that appeared on subsequent, post-collaborative tests of individual memory downstream and further lessened the overall amount of forgetting that occurred across delay.

As an aside, it is useful to keep in mind that the rationale outlined here for the differences in the role of rehearsal for repeated study and repeated retrieval applies to typical encoding procedures (such as those instantiated in the present study) and may not be entirely universal, in that experimental instructions that enforce extensive organization (e.g., instructing participants to relate items during study or study materials that demand extensive relational processing) could reduce or eliminate the differences between these learning methods. Similarly, the role of retrieval organization is also sensitive to how memory is tested; for example, performance on a recognition task that provides studied information does not depend on retrieval organization for successful performance and therefore could be less sensitive to the differences examined here. The critical point here is to elucidate the consequences of the learning methods, which differentially promote retrieval organization, under the present experimental conditions on the patterns of individual, collaborative, and post-collaborative recalls.

Concluding Comments

Our study integrated elements from a variety of cognitive literatures to answer fundamental questions about how groups work together to reconstruct the past and how such collaboration influences individual memory across time. Through the combination of paradigms drawn from the repetition literature with those used to examine the testing effect, we were able to examine how one's learning method prior to collaboration could alter the presence of collaborative inhibition by influencing the group's susceptibility to retrieval disruption. In the case of the repeated retrieval learning method, the strengthening of one's own idiosyncratic organization of the studied material protected against the effects of retrieval disruption and allowed participants to gain the most in terms of re-exposure benefits during collaboration. This, in turn, improved those participants' post-collaborative individual recall. Such findings could only have been discovered through the integration of different literatures spanning collaborative and individual memory domains into one design. In addition, the inclusion of a repeated study learning method along with the presence of a delay between learning method and retrieval allowed for the emergence of cross-cuing effects that might have otherwise remained obscured. Finally, the inclusion of different learning methods and two different delays simultaneously enabled us to examine a related yet distinct question in the individual memory literature pertaining to the nature of the testing effect. The results of our study show the advantages of bringing together different literatures in order to uncover findings that span both collaborative and individual memory domains of inquiry.

The results of our study point to important cognitive principles that may be relevant for the use of group study practices. If people plan on working together as a part of a group, it is clear that securing one's own conceptual organization of the learned material is important to minimize disruption and to benefit from collaboration. And our findings reported in this article demonstrate that one effective way to achieve strong organization is for people to repeatedly test themselves on the material on which they plan to collaborate. Such repeated testing is an effective tool to prevent disruption during collaboration and to gain the most in terms of re-exposure from the other group members' contributions. By engaging in such a repeated retrieval learning method, the group will be able to recall up to its full potential during collaboration and the later memory of each individual member will be improved as a result of previous collaboration. Several aspects of our design revealed the ways in which repeated study can also confer benefits. For example, at long delay the repeated study method also produced post-collaborative gains. Taken together, when the antecedent learning methods produce learning that is less susceptible to disruption, post-collaborative learning improved. In closing, we also note that while the delays used in the present study were calibrated to the specific learning conditions used here, this study provided the empirical and theoretical foundations for expanding future investigations to various learning, delay, and testing questions of both theoretical and practical value.

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(*Appendix follows*)

Appendix

Calculation of Nominal Group Recall

To calculate a nominal group score, the nonoverlapping responses of a group of individuals who recalled by themselves are combined to form a group that is equal in size to the collaborating group. For example, if Person 1 recalled *apple, boy, cat,* and *dairy*; Person 2 recalled *apple, boy*, and *elf*; and Person 3 recalled *apple, fabric, ghoul, hat*, and *puzzle*, then the nominal group recall would be equal to nine unique items (*apple, boy, cat, dairy, elf, fabric, ghoul, hat*, and *puzzle*).

Table A1
Means (and Standard Errors) for Uncorrected Recall Across the Four Conditions for Both Short and Long Delay Groups

	Short delay				Long delay			
	Repeated study		Repeated retrieval		Repeated study		Repeated retrieval	
Learning method	Nom	Coll	Nom	Coll	Nom	Coll	Nom	Coll
Recall								
Phase 4	.86	.71	.74	.69	.77	.70	.68	.67
[(N)-(Recall of C-Recall)]	(.02)	(.02)	(.03)	(.02)	(.02)	(.03)	(.03)	(.01)
Phase 5	.53	.53	.44	.54	.45	.51	.41	.48
Following I (N) or C	(.02)	(.02)	(.03)	(.02)	(.02)	(.02)	(.02)	(.02)

Note. Nom = Nominal; Coll = Collaborative; I (N)-Recall = Nominal Group Recall; C-Recall = Collaborative Group Recall.

Table A2
Means and Standard Errors for the Recall Intrusion Scores Across the Four Conditions for Both Short and Long Delay Groups

	Short delay				Long delay			
	Repeated study		Repeated retrieval		Repeated study		Repeated retrieval	
Learning method	Nom	Coll	Nom	Coll	Nom	Coll	Nom	Coll
Phase 4–Group Recall								
I (N)-Recall or C-Recall	1.92 (0.40)	0.83 (0.30)	3.91 (0.90)	1.17 (0.39)	3.92 (0.81)	0.25 (0.13)	3.82 (0.59)	1.17 (0.30)
Phase 5–Individual Recall								
Following I (N) or C	1.19 (0.23)	0.94 (0.19)	2.00 (0.46)	1.36 (0.27)	1.42 (0.33)	0.81 (0.16)	1.44 (0.30)	1.11 (0.18)

Note. Nom = Nominal; Coll = Collaborative; I (N)-Recall = Nominal Group Recall; C-Recall = Collaborative Group Recall.

Received June 4, 2010
Revision received March 29, 2011
Accepted April 1, 2011 ■