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Collaboration Changes Both the Content and the Structure of Memory: Building the Architecture of Shared Representations

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Memory research has primarily focused on how individuals form and maintain memories across time. However, less is known about how groups of people working together can create and maintain shared memories of the past. Recent studies have focused on understanding the processes behind the formation of such shared memories, but none has investigated the *structure* of shared memory. This study investigated the circumstances under which collaboration would influence the likelihood that participants come to share both a similar content and a similar organization of the past by aligning their individual representations into a shared rendering. We tested how the frequency and the timing of collaboration affect participants' retrieval organization, and how this in turn influences the formation of shared memory and its persistence over time. Across numerous foundational and novel analyses, we observed that as the size of the collaborative inhibition effect—a counterintuitive finding that collaboration reduces group recall—increased, so did the amount of shared memory and the shared organization of memories. These findings reveal the interconnected relationship between collaborative inhibition, retrieval disruption, shared memory, and shared organization. Together, these relationships have intriguing implications for research across a wide variety of domains, including the formation of collective memory, beliefs and attitudes, parent–child narratives and the development of autobiographical memory, and the emergence of shared representations in educational settings.

Keywords: collective memory, shared memory, shared retrieval organization, collaborative inhibition, retrieval disruption

Cognitive research on human memory has primarily focused on how individuals form and maintain memories across time. Yet people often discuss the past and their knowledge of the world with others on a daily basis, from friends and family reminiscing about shared past experiences to faculty members attempting to reconstruct what happened at a previous meeting. Researchers have become interested in how such collaborative discussions affect people's memories of the past. Although recent research has demonstrated how the act of collaboration can influence both the content (or, what is remembered) and structure (or, how these memories are organized) of people's later individual memory, little is known about how groups of people by working together may create and maintain shared memories and shared organization of these memories by *aligning* their individual renderings of the past.

The manner in which people come to share similar memories has important implications for a wide variety of research domains. For example, social psychologists have long acknowledged the role of accessible content retrieved from memory as one of the primary determinants involved in belief and attitude formation (Wyer & Albarracin, 2005). If people were to share similar memories of relevant knowledge, they may subsequently form similar beliefs and attitudes based on accessing that commonly available knowledge, a hypothesis we are currently testing in empirical work. Developmental psychologists may be interested in whether parent–child conversations lead to shared narrative representations of the past as a result of children's internalization of their parents' narrative method for organizing aspects of autobiographical experience into a cohesive whole (Nelson & Fivush, 2004; Wang & Fivush, 2005). This process of internalization of their parents' narrative method is related to what Vygotsky would call the psychological instantiation of a social interactional process (Vygotsky, 1978), and, as we discuss in the Theoretical Implications section of the General Discussion, may be exemplified by the presence of shared organization between children and their parents. There are also important educational implications for researchers interested in understanding how students taught in the same classroom by the same teacher may come to form a shared memory of the studied material. Such a teaching environment likely promotes a collective, commonly accepted representation of the material, and the implications of this may have an effect on the emergence of creative solutions to problems involving the material. Another educationally relevant issue concerns the effectiveness of cooperative learning techniques, where students work together to achieve a variety of shared learning goals (e.g., Johnson, Johnson, & Stanne, 2000). Our study provides important insight into understanding why cooperative learning may result in

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sustained and shared knowledge among students, particularly when teachers use more "conceptual cooperative learning methods" that require restructuring of lessons and activities. Thus, understanding the mechanisms that give rise to shared memory, as well as providing a quantitative method for capturing the presence of the shared structures of these representations, has widespread research and applied implications.

Outside of psychology, shared memory has traditionally been conceptualized as "collective memory" and studied in domains ranging from sociology (e.g., Halbwachs, 1950/1980) to anthropology (e.g., Cole, 2001) and history (e.g., Bodnar, 1992). Given the wide variety of approaches to studying collective memory, there is an equally wide range of definitions with no formal consensus (see Wertsch & Roediger, 2008, who define collective memory in terms of its relation to similar concepts). A prevalent view discussed in recent psychological work is the role collective memory plays in the emergence and persistence of a cultural identity within groups (Hirst & Manier, 2008; Zaromb, Butler, Agarwal, & Roediger, in press).

In empirical, laboratory-based research in psychological science, collective memory is operationalized without reference to identity but with a focus on understanding the mechanisms by which shared memories develop (e.g., Brown, Coman, & Hirst, 2009; Cuc, Koppel, & Hirst, 2007; Cuc, Ozuru, Manier, & Hirst, 2006; Stone, Barnier, Sutton, & Hirst, 2010). In the present study, we leveraged this laboratory definition, investigating the shared memory component of collective memory, and we developed methods to quantitatively capture how shared memories form, organize, and persist. Because little is known about the organizational components of shared memory, this foundational step is crucial to understanding in the laboratory the building blocks of how people's memories come to overlap. Such work then positions the field to examine in the future the broader notion of the role that overlapping memory plays as part of a group's identity (e.g., Zaromb, Butler, Agarwal, & Roediger, in press).

Our conceptualization of "collective memory as shared memory" already has precedence in the psychological literature, as we briefly noted above. Specifically, to encapsulate the idea that collective memories are formed as a result of individuals engaged in group recounting of the past, some researchers have defined collective memory as the overlap in individuals' memories after they have engaged in collaborative, conversational recall (Cuc et al., 2006), in other words, the shared or similar memories that form among group members. This definition highlights the importance of discussing the past with others on the formation of shared memories. As such, researchers have calculated the formation of shared memories by measuring the overlap in people's memories following collaboration and comparing it with the overlap that existed prior to collaboration. In this study, we adopt this empirical definition used in previous research (e.g., Cuc et al., 2006) but refer to it as shared memory.

A growing body of empirical evidence has begun to examine the various mechanisms involved in the formation of shared memories, and these mechanisms have recently been integrated within a theoretical framework for how collaborative discussions potentially shape shared memory (Rajaram, 2011; Rajaram & Pereira-Pasarin, 2010). However, much remains unknown about the extent or stage of collaboration in an ongoing retrieval process that is most effective for their formation. Importantly, there is also a complete absence of empirical research on the influence of an individual's pre-collaborative memory, particularly with regard to their preexisting way of organizing the memory they bring with them to conversations with others, on the formation of shared memories. This study was designed to address these critical gaps in the literature and to break new ground in understanding how shared memories develop, organize, and are maintained across time.

The Nature of Retrieval Organization

In cognitive theories, memory organization has been conceptualized in terms of *retrieval organization*, or the degree to which people systematically cluster information together during recall according to some strategy that allows the information to be better remembered across time. For example, such clustering can take the form of recalling words from the same taxonomic category together (e.g., automobiles, four-legged animals, etc.; Bousfield, 1953). Importantly, even in the absence of an externally imposed organization (such as elicited by categorized stimuli), participants are still likely to impose their own idiosyncratic organization on the study material, chunking information into higher order conceptual units across time in a process known as *subjective organization* (Gates, 1917; Tulving, 1962).

Research on both individual and group memory support the notion that retrieval organization may play an important role in shared memory. First, findings from the individual memory literature have shown that information that is better organized survives longer across time (Mulligan, 2005; Puff, 1979; Zaromb & Roediger, 2010; see also Congleton & Rajaram, 2012; Luhmann, Congleton, Zhou, & Rajaram, 2014), as information that has been chunked into clusters is easier to retrieve compared with non-clustered information (Miller, 1956; Zaromb & Roediger, 2010; see also Congleton & Rajaram, 2012). Second, retrieval organization of individual group members has been found to play a critical role in shaping collaborative group processes—a precursor for the formation of shared memory—both in immediate recall and after some delay between learning and recall (Congleton & Rajaram, 2011). Thus, it is important to study the role of retrieval organization not only in terms of the relationship between organization at the individual level and the collaborative process (as we did in our previous research; Congleton & Rajaram, 2011), but just as critically in terms of the emergence of retrieval organization at the group level and its relation to the formation of shared memories and their persistence over time, as we do in the present study.

The *persistence of shared memory* refers to the continued collective retrieval of the information during each subsequent retrieval opportunity. Thus, the memory continues to "persist" across time if all group members who previously collaborated retrieve it during every subsequent retrieval opportunity. The proposed influence of retrieval organization on shared memory persistence follows from the fact that it has already been shown to affect the persistence of individual memory. Because previous research has demonstrated that individual and group memory often share many of the same underlying principles (Weldon & Bellinger, 1997), it is reasonable to hypothesize that retrieval organization has implications for shared memory. Thus, the time is ripe for testing the role of retrieval organization on the formation and persistence of shared memory. Of course, one of the challenges of examining the persistence of memory in the laboratory, whether individual or shared, is the likely presence of floor effects in the data following a long delay between initial study and final recall (e.g., 1 week). However, as the conditions of the present study design were amenable to examining shared memory persistence, we report the patterns observed where they are informative to the goals of this study.

Collaborative Recall Paradigm

We tested the emergence of shared memory and shared organization empirically by means of a paradigm designed to assess what happens when people collaborate together to recall the past: *the collaborative recall paradigm*. Arising from a cognitive psychological tradition, collaborative recall research is the relatively recent, but a predominant and effective, approach to studying group memory processes (Weldon, 2001; Weldon & Bellinger, 1997). Early work on collaboration demonstrated that although collaborative groups recall more than individuals working alone, the groups typically recall less than if the individuals comprising that group had worked individually and had their non-redundant responses pooled, forming a post hoc group known as a *nominal group*. The phenomenon of reduced recall in collaborative groups is known as *collaborative inhibition* (Weldon & Bellinger, 1997). Although social loafing (Latane, Williams, & Harkins, 1979), or diffusion of responsibility, during group recall seems like a plausible explanation of this outcome, extant research has failed to support this interpretation (Weldon, Blair, & Huebsch, 2000). The prevailing theory of collaborative inhibition is that it is caused by the disruption of each individual person's way of organizing the study materials during recall. In situations in which there are many ways for people to organize a set of studied materials, the greater the probability that these individuals engaged in collaboration will possess divergent ways of idiosyncratically organizing the material. As a result of such divergence, people who possess different organizations coming into a collaborative situation actually will hinder one another in their ability to reconstruct the material, a phenomenon known as *retrieval disruption* (Basden, Basden, Bryner, & Thomas, 1997). This increases the likelihood of less information being produced compared to if all of the participants shared the same organization coming into the conversation.

Linking Collaborative Recall Processes to Shared Memory

The Role of Retrieval Disruption

The operation of retrieval disruption during collaboration has proved to be critical in understanding how shared memories form. In previous research, we have found that the influence of collaboration on people's later recall, or their "post-collaborative individual recall," may depend on the operation of several factors occurring during collaboration (e.g., Blumen & Rajaram, 2008; Congleton & Rajaram, 2011), and some of these factors, such as retrieval disruption, may thus be involved in the mediation of shared memory formation (see Rajaram & Pereira-Pasarin, 2010; Stone, Barnier, Sutton, & Hirst, 2010). For example, we have found that participants who collaborate in the recall of a list of words have greater overlap in their post-collaborative individual recall (i.e., more overlapping or shared memories; Blumen & Rajaram, 2008). Furthermore, collaboration during retrieval seems to be particularly powerful compared with collaboration during encoding in giving rise to shared memories (i.e., greater overlap among post-collaborative memories) among the former collaborators (Barber, Rajaram, & Fox, 2012).

These results indicate that shared memory formation may be closely tied to the cognitive mechanisms that become active when participants work together to recall memories they had individually formed and idiosyncratically organized after initial exposure (see Rajaram & Pereira-Pasarin, 2010). Specifically, the results intimate about the relationship between retrieval organization and shared memory formation. Given that collaborative retrieval promotes shared memory formation, we hypothesized and tested in this study that this likely occurs because collaborative discussion disrupts each participant's idiosyncratically organized material. However, at the same time, a group-level organization is formed out of the disrupted organization of each individual involved in the collaborative discussion. When participants subsequently attempt to recall the studied material individually (on their post-collaborative recall), they can either attempt to reproduce their original organization (which was just disrupted) or they can attempt to reconstruct the organization that the group as a whole produced. We argue that as the size of the collaborative inhibition effect increases (and thus the amount of retrieval disruption increases), participants will be more likely to adopt the organization of the group on their later individual recall as compared with recreating their original, idiosyncratic organization. Because all former collaborators are likely to engage in this process, this should lead to the participants sharing not only *the same overlapping content* (i.e., shared memories) but also *the same overlapping organization* of that information that newly developed during collaboration (i.e., *shared organization*, or the structure of shared memories). To our knowledge, this question has remained entirely untested.

The Frequency and Timing of Collaboration

As the collaborative process is hypothesized to play a key role in shared memory formation and persistence, an important question that emerges is what particular variables might modulate the level of shared memory that forms as a result of collaboration. The frequency and timing of collaboration might be among the most fundamental factors to consider, as these circumstances characterize collaborative interactions routinely, and yet we still understand very little about how such basic conditions shape shared memory and shared organization. As such, we predict that the more times a group of people collaborate together (Multiple Collaboration), the more likely a strong group-level organization will emerge (Weldon & Bellinger, 1997). As a result, participants should be more likely to adopt the organization of the group on their post-collaborative recall, producing a greater amount of shared memories and shared organization compared with participants who only collaborated once.

In addition, the timing of collaboration within a series of recalls could also influence the likelihood that people will come to share similar content and structure in their memory. Specifically, it is likely that a collaborative session happening later in a series of recalls (i.e., Late Collaboration) would lead to greater memory similarity among collaborators than a collaborative session that happens earlier in a series of recalls (i.e., Early Collaboration). This is because of the recent availability of the collaborative, group-level organizational structure. This is compared with a situation in which there is an intervening individual recall session between collaboration and one's final individual recall, where it is likely that participants will overcome the impact of group-level organization because they now have an opportunity to revert to their preferred, idiosyncratic organization of what they had studied. This study was designed to answer these novel yet fundamental questions and thus included Early, Late, and Multiple Collaboration conditions to examine these possibilities, all of which were compared with a control condition in which participants never collaborated but performed recall an equal number of times to the other conditions.

One interesting additional question that arises from this line of reasoning is whether the amount of shared memory formation and shared organization that develops among former collaborators is tied to the extent to which participants rely on their past retrievals (which include both individual and collaborative recalls). If participants are not recreating their previous collaborative recall session, then it is possible they may fail to develop a large amount of shared memory and shared organization as they are not accessing the commonly available structure that formed during collaboration. Thus, it is important to examine the extent to which a participant's final individual recall is dependent on the content and structure of their earlier recalls. We can then examine whether this dependency modulates the amount of shared memory and shared organization that develops. As no method for computing shared retrieval organization of groups, nor for analyzing the dependency of a person's current recall upon the content and structure of previous recalls is available to our knowledge, we developed novel analyses to investigate these phenomena. We call these analyses the Shared Organizational Metric Analysis (SOMA) and the Origin Analysis, respectively (see the Results section for details).

To summarize our predictions, in this study we were interested in examining how the collaborative process (and specifically, retrieval disruption operating within collaboration) may give rise to the formation and persistence of shared memories and shared organization. We also wanted to examine whether the size of the collaboration inhibition effect influences the amount of shared memories and organization that forms, and whether the frequency and timing of collaboration influences this relationship. We predict that as the size of the collaborative inhibition effect increases, the greater the amount of shared memories and shared organization that will develop among participants who have formerly collaborated. We also predict that the more times participants collaborate, the greater the amount of shared memory and shared organization that will develop, and that participants who collaborate later within a series of recalls will develop a greater amount of shared memory and shared organization compared with participants who collaborate earlier.

Method

Materials

The stimuli consisted of a list of 120 categorized words, with eight categories and 15 exemplars per category. These stimuli and this list length and structure allowed for many potential ways in which the exemplars could be clustered together in recall and made it possible to separately identify idiosyncratic and group clusters during post-collaborative recall. The words were taken from the van Overschelde, Rawson, and Dunlosky (2004) word norms. We excluded the top two to three exemplars per category in order to prevent such items from dominating recall and retrieval organization patterns, as that would have made it difficult to separately identify clusters from a participant's post-collaborative recall that had originated from either their earlier individual recall or their earlier collaborative recall session (which is important for conducting the Origin Analysis).

The selection of categorized words as stimuli was guided by a number of important reasons. One, these stimuli have been found to lend themselves to the calculation of retrieval organization scores (e.g., Roenker, Thompson, & Brown, 1971; Sternberg & Tulving, 1977). Thus, the use of these stimuli provides a quantitative measure of the relation among collaboration, retrieval organization, and shared memory formation. Two, although more naturalistic stimuli may consist of past narratives or stories, previous research has shown that individuals also tend to impose organization upon conceptually related stimuli (Bousfield, 1953). Thus, related words invoke organizational processes and enable generalizable quantification across studies. Further, as the principles involved in the formation of organization around these categorized stimuli are well known, their use aided in our examination of the relationship of this well-established principle in a new and exciting area of memory research and enabled us to develop new quantitative measures of retrieval organization in group memory. These words allow us to take the foundational steps in establishing principles and methods that can be applied to more complex or ecologically valid materials in future research (e.g., Harris, Keil, Sutton, Barnier, & McIlwain, 2011). Furthermore, any potential concerns that word stimuli (even those that are highly structured in conceptual terms) may be artificial, and that any results derived from them may not generalize, are further mitigated by the reports that even in the absence of an externally imposed organization, participants impose their own subjective organization upon whatever stimuli (e.g., even unrelated words) they encounter (Gates, 1917; Mulligan, 2002; Tulving, 1962). Thus, categorized word stimuli combined the best of various options for the present purposes: These stimuli possess externally imposed conceptual structure (like a narrative); lend themselves to the natural inclination of subjects to impose a subjective organization; have been successfully used to quantitatively measure retrieval organization in recall; and are quantifiable for the calculation of collaborative inhibition, shared memory, and the novel shared retrieval organization measures.

Participants

A total of 144 participants at Stony Brook University volunteered in this study for experimental credit. There were 12 triads of participants per condition across four between-subjects conditions.

Design and Procedure

The experiment consisted of four conditions: Control (no collaboration), Early Collaboration, Late Collaboration, and Multiple

Collaboration. Table 1 presents the full design and sequential nature of the procedure described here.

When the participants arrived in the lab for their first session, they were randomly assigned to one of those four conditions. At the beginning of the experiment, all participants were exposed to the study stimuli via a PowerPoint presentation, which they studied individually. Afterwards, all participants completed a spatial distractor task for 7 min (i.e., maze completion), again individually. Following the completion of this task, all participants took an individual recall test, in which they were asked to write down on a blank sheet of paper as many of the study words they could produce. They had 7 min to produce as much as possible. This recall phase served as the baseline measure. After completing the first individual recall (pre-collaborative recall), the procedure began to differ depending on the condition.

Participants in the control condition took three additional individual recall tests in a row following the same format given above. Collaborative groups in the remaining three conditions were formed by randomly assigning three individuals into one group with the restrictions that they had not known each other before. Before beginning a collaborative session, the participants were asked to speak their subject numbers (e.g., 102, 203, etc.), along with a short sentence, aloud into a tape recorder that enabled us to have a record of what each participant recalled. They were told that even though all three would be working together during recall and would have everyone's recalled items in full view, only one person (i.e., the scribe) would be recording their answers on the sheet.[1] Participants in the Early Collaboration condition were formed into a group of three members and were instructed that they would work together to recall as many items as possible. As in the individual recall sessions, they also had 7 min to produce as much as they could, which is sufficient for the groups to complete their recall attempt (Congleton & Rajaram, 2011). They were allowed to recall their words in a free-flowing format with no turn-taking structure, and they were told that if any disagreements arose between them about whether or not a particular word was actually studied, it was up to them to arrive at a solution. Afterwards, participants in the Early Collaboration condition were asked to recall individually two more times following the instructions outlined above. For the participants in the Late Collaboration condition, after the initial individual recall, they were asked to recall individually once again following the same instructions outlined above. Afterwards, they were formed into a collaborative group and asked to recall according to the instructions outlined above. Finally, they recalled individually once more. For participants in the Multiple Collaboration condition, after initially recalling individually, they were put into a collaborative group and asked to recall collaboratively twice in a row following the instructions outlined above. Afterwards, they recalled individually once more. This individual recall—administered at the same stage in all conditions—provided the data for the calculation of the content and structure of shared memory as a function of the preceding frequency and timing of collaboration. Following the completion of these retrieval sequences, all participants were asked to leave the lab and return exactly 1 week later to complete the second part of the study. When the participants returned, they were asked to recall individually according to the instructions outlined above. This final individual recall session provided the data for measuring the persistence of shared memory. Afterwards, all participants received a full written and verbal debriefing as to the goals of the study.

Table 1
Experimental Design for the Four Conditions

	Control	Early Collaboration	Late Collaboration	Multiple Collaboration
Phase 1	Study	Study	Study	Study
Phase 2	Distractor	Distractor	Distractor	Distractor
Phase 3 (R1)	I-Recall	I-Recall	I-Recall	I-Recall
Phase 4 (R2)	I-Recall	C-Recall	I-Recall	C-Recall
Phase 5 (R3)	I-Recall	I-Recall	C-Recall	C-Recall
Phase 6 (R4)	I-Recall	I-Recall	I-Recall	I-Recall
		Delay of 1 week		
Phase 7 (R5)	I-Recall	I-Recall	I-Recall	I-Recall

Note. I-Recall = Individual Recall; C-Recall = Collaborative Recall; R1 = Recall 1; R2 = Recall 2; R3 = Recall 3; R4 = Recall 4; R5 = Recall 5.

Results

The goal of this study was to examine the influence of collaboration on the formation and persistence of shared memories and shared organization among participants who previously collaborated. The design of this study allowed us to examine the impact of both the frequency of collaboration as well as the timing of collaboration within a series of recalls on both the content and structure of memory. Unless otherwise indicated, all pairwise comparisons are adjusted for a Bonferroni correction.

The design of the study allowed us to calculate shared memory and shared organization in two separate ways: (a) by calculating the scores across the three individuals who collaborated (i.e., triads) and (b) by calculating the scores in terms of three sets of two individuals within each triad (i.e., dyads). As the minimum number of participants required for the calculation of shared memory is two (i.e., a dyad of individuals), and the data from both dyads and triads revealed similar patterns, we present our results based on the dyadic data in the interest of economy.[2] This fundamental unit of measurement also provided more robust data than triads (i.e., it provide a greater N in the calculation of the analyses).

Baseline Levels of Shared Memory

Prior to examining the influence of collaboration, baseline levels of shared memory and shared organization were assessed (Recall 1, see Table 2). Although the definition of shared memory we adopted above seems to imply that participants only exhibit overlap in their memory after engaging in collaborative discussion, it is possible that they may possess memory overlap even prior to collaboration because all of them were exposed to the same information during the study episode. To examine baseline levels of shared memory, a one-way between-subjects analysis of variance (ANOVA) was conducted. The

[1] See Blumen and Rajaram (2008) for evidence that scribe status does not affect recall in collaborating groups.

[2] Where relevant, we equate triad-to-triad comparisons between shared memory and collaborative inhibition.

Table 2
Means and (Standard Errors) for Baseline (Recall 1) Levels of Shared Memory Prior to Collaboration for the Number of Items Recalled and Shared Organization Across Conditions

	Control	Early Collaboration	Late Collaboration	Multiple Collaboration
Shared memory	15.19 (.79)	17.44 (1.04)	15.25 (.90)	13.53 (.85)
SOMA	1.28 (.26)	1.53 (.23)	1.45 (.29)	1.25 (.18)

Note. SOMA = Shared Organizational Metric Analysis.

results indicated there was a significant main effect of group, $F(3, 140) = 3.20$, $MSE = 29.03$, $p = .03$, $d = .04$. However, this discrepancy among the conditions on Recall 1 is not problematic because the analyses examining the formation of shared memory (and shared organization) on Recall 4 are conducted as analyses of covariance (ANCOVAs). As such, the baseline levels of shared memory are held constant across conditions.

The Influence of Collaboration on Shared Memory Content

We first tested how collaboration influences the formation of shared memories. We examined this by calculating the degree to which participants share correctly recalled items (i.e., have overlapping recollections) with their fellow partners following collaboration (or with their nominal group in the case of the control condition).[3] In order to control for baseline levels of shared memory, we conducted an ANCOVA in which the dependent variable was shared memory at Recall 4, the independent variable was group, and the covariate was shared memory at Recall 1.[4] Prior to conducting the ANCOVA, we examined the assumption of homogeneity of regression by testing the interaction of the independent variable with the covariate. This interaction was small (increment in $R^2 = .006$) and was not significant ($F < 1$). The ANCOVA yielded a significant difference among the four conditions, $F(3, 139) = 46.90$, $MSE = 55.60$, $p < .001$; effect size (partial η^2) = .503. Adjusted means and standard errors for the four conditions are shown in Figure 1. Follow-up pairwise comparisons indicated that participants in the Early Collaboration ($M = 31.46$, $p < .001$, $d = 1.24$), Late Collaboration ($M = 35.34$, $p < .001$, $d = 1.77$), and Multiple Collaboration ($M = 42.74$, $p < .001$, $d = 2.75$) conditions all produced significantly better levels of shared memory compared with participants in the control condition ($M = 22.15$). In addition, the Multiple Collaboration condition resulted in significantly greater shared memory formation than either the Early ($p < .001$, $d = 1.49$) or Late Collaboration conditions ($p < .001$, $d = .99$). There was no significant difference between Early and Late Collaboration ($p = .19$, $d = .52$).

The next major question of interest was how collaboration influenced the persistence of shared memory. This analysis focused on shared memory in Recall 5 that occurred after a 1-week delay.[5]

The means and standard deviations for shared memory persistence (Recall 5) across the four conditions are shown in Figure 1. A one-way between-subjects ANOVA, with group as the factor, revealed a main effect of group on shared memory at Recall 5, $F(3, 140) = 21.92$, $MSE = 40.18$, $p < .001$, $d = 1.44$. Follow-up pairwise comparisons reveal that control participants ($M = 10.72$) had significantly less shared memory persistence compared with Early ($p < .001$, $d = .98$), Late ($p < .001$, $d = 1.72$), and Multiple Collaboration participants ($p < .001$, $d = 1.91$). In addition, Multiple Collaboration participants ($M = 22.03$) had significantly greater amounts of shared memory persistence compared with Early Collaboration participants ($M = 17.39$; $p = .01$, $d = .65$), but an equivalent amount compared with Late Collaboration participants ($M = 20.14$; $p = 1.00$, $d = .32$). Finally, there was no difference between Early and Late Collaboration participants for the amount of shared memory persistence ($p = .41$, $d = .41$).

The Modulating Effect of Collaborative Inhibition on the Formation of Shared Memory

One of the key predictions of this study was that the amount of collaborative inhibition would affect the amount of shared memory and shared organization that formed following collaboration. To test this prediction, we examined the presence of collaborative inhibition at two time points (i.e., Recall 2 and/or Recall 3). The size of the collaborative inhibition effect was calculated by subtracting the mean recall accuracy of the collaborative condition in question (i.e., Early, Late, or Multiple) from the mean recall accuracy of the nominal condition at either Recall 2 or Recall 3 (i.e., Nominal group recall – Collaborative group recall = size of collaborative inhibition effect). As can be seen in Table 3, the size of the collaborative inhibition effect for Early Collaboration participants during Recall 2 was .06 (.66 − .60 = .06), for Multiple Collaboration participants during Recall 2 was .09 (.66−.57 = .09), for Late Collaboration participants during Recall 3 was .07 (.67−.60 = .07), and for Multiple Collaboration participants during Recall 3 was .04 (.67−.63 = .04). We observed significant collaborative inhibition at Recall 2 for both the Early and Multiple Collaboration participants, and at Recall 3 for the Late Collaboration participants, while there was no significant effect at Recall 3 for the Multiple Collaboration participants (a finding that replicates previous research examining multiple instances of collaboration; Blumen & Rajaram, 2008).[6] These results are based on data

[3] As participants could potentially share all recalled items with their partners, the upper-bound on the shared memory calculation was equivalent to the length of the study list (i.e., 120 items).

[4] The same pattern of results was observed when all of the ANCOVAs described in this experiment were run as simple ANOVAs. Therefore, we took the more conservative approach of controlling for baseline levels in reporting these results and present only the results of the ANCOVAs.

[5] It is important to keep in mind that the methodological constraints needed to achieve below-ceiling performance at immediate testing (Recalls 1–4) and the need to create sufficient delay (1 week) to study persistence of memory led to low shared memory performance levels after the 1-week delay (9%–18% overlap in participants' total recall). Therefore, these data should be interpreted cautiously. Nonetheless, a number of interesting patterns emerged from these analyses that provide useful insights into the decline and persistence of shared memory across different collaboration histories.

[6] Although the p value for the size of the collaborative inhibition effect for the Early Collaboration participants during Recall 2 was .06 based on a two-tailed analysis (as can be seen in Table 3), the prediction for collaborative inhibition is in fact one-tailed based on a large set of published findings (e.g., Andersson, Hitch, & Meudell, 2006; Basden, Basden, Bryner, & Thomas, 1997; Blumen & Rajaram, 2008; Congleton & Rajaram, 2011; Finlay, Hitch, & Meudell, 2000; Harris et al., 2011; Takahashi & Saito, 2004; Weldon & Bellinger, 1997; Yaron-Antar & Nachson, 2006). As such, a one-tailed test is justified under the present circumstances, and the analysis yields a significant collaborative inhibition effect for the Early Collaboration participants during Recall 2 as well.

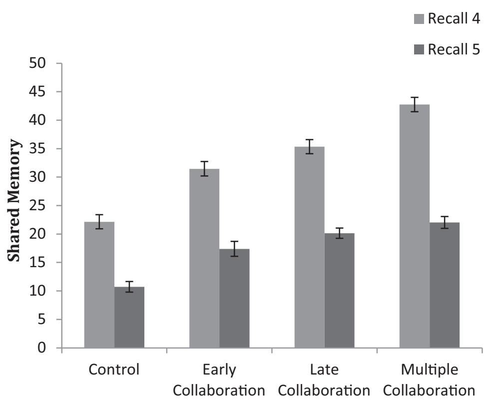

Figure 1. Shared memory at Recall 4 (immediate) and Recall 5 (after 1-week delay). The figure depicts adjusted means for each condition. Error bars represent standard errors.

from the triads (i.e., rather than dyads within the larger triad), as this is the standard approach in the collaborative memory literature and is considered more effective than the smallest unit of dyads at detecting the effects of retrieval disruption and collaboration within a group (Basden, Basden, & Henry, 2000; Thorley & Dewhurst, 2007).

Concerning the calculation of the collaborative inhibition effect, one point worth mentioning is that there was an initial difference in mean recall accuracy among the four conditions: Namely, the Early Collaboration participants had marginally significantly better recall accuracy at Recall 1 compared with the other conditions (all *p*s $> .05$; see Table 4). There were no differences in recall accuracy between any of the other three conditions. As such, this initial difference in recall accuracy for the Early Collaboration participants would only affect the calculation of collaborative inhibition at Recall 2 for the Early Collaboration participants. As was mentioned above, the collaboration inhibition effect in the Early Collaboration condition (6%) was somewhat smaller than this effect in the Multiple Collaboration condition (9%), but comparable to this effect (6%) in the Late Collaboration condition. So, the fluctuations in the size of the collaborative inhibition effect were small or nil across conditions. Further, if higher initial recall accuracy for the Early Collaboration participants did provide a recall advantage for them during collaboration, it stacks the deck against our prediction. That is, if the Early Collaboration participants did not possess this initial recall advantage going into collaboration, then their recall level during collaboration itself (i.e., Recall 2) might have been even lower compared with the nominal group than is the case at present, and such a pattern would have produced a larger collaborative inhibition effect than what we currently observe. That we observe a significant collaborative inhibition effect in the Early Collaboration condition (that was comparable to the other conditions) despite a slightly higher performance during Recall 1 in this condition indicates that the collaborative inhibition effects across conditions were not confounded by Recall 1 levels.

Table 3
Mean Size of the Collaborative Inhibition Effect for Early Collaboration, Late Collaboration, and Multiple Collaboration Participants During Recalls 2 and 3

	Early Collaboration	Late Collaboration	Multiple Collaboration
Recall 2	.06 ($p = .06$)		.09 ($p = .01$)
Recall 3		.07 ($p = .05$)	.04 ($p = .24$)

Note. The size of the collaborative inhibition effect is calculated by subtracting the mean recall accuracy of the collaborative condition in question (i.e., Early, Late, or Multiple) from the mean recall accuracy of the nominal condition at either Recall 2 or Recall 3 (i.e., Nominal group recall − Collaborative group recall = size of collaborative inhibition effect).

Table 4
Means and (Standard Errors) for Individual Recall Accuracy Across Conditions

	Control	Early Collaboration	Late Collaboration	Multiple Collaboration
R1	.31 (.01)	.35 (.02)	.32 (.01)	.30 (.01)
R2	.33 (.01)		.35 (.01)	
R3	.35 (.01)	.45 (.01)		
R4	.37 (.02)	.46 (.02)	.45 (.02)	.50 (.02)
		Delay of 1 week		
R5	.24 (.01)	.31 (.02)	.32 (.02)	.34 (.01)

Note. R1 = Recall 1; R2 = Recall 2; R3 = Recall 3; R4 = Recall 4; R5 = Recall 5.

Next, we examined whether the finding that collaboration influences the amount of shared memory formed is related to the size of the collaborative inhibition effect. If this turned out to be the case, these results would demonstrate that the more people experience a disruption of their own idiosyncratic manner of organizing the past (the current explanation for the collaborative inhibition effect; Basden et al., 1997), the more likely they are to share similar content in their memory following collaboration. To examine this possibility, we conducted a series of regression analyses examining the relationship between the size of the collaborative inhibition effect and the amount of shared memory that develops afterwards. For these regressions that examined the relationship between the size of the collaborative inhibition effect and the amount of shared memory and shared organization that develops (see below for regressions involving shared organization), we conducted the regressions on the triadic data in order to equate the size of the variables.

First, we conducted a regression analysis in which the amount of shared memory formed during Recall 4 was the criterion variable and the size of the collaborative inhibition effect at Recall 2 was the predictor variable (for the Early and Multiple Collaboration participants). The overall R^2 was .27, $F(1, 22) = 8.18$, $p = .009$; effect size (f^2) = .37, indicating a strong relationship between these two variables. Likewise, another regression analysis was conducted with the amount of shared memory formed during Recall 4 as the criterion variable and the size of the collaborative inhibition effect at Recall 3 serving as the predictor (for the Late and Multiple Collaboration participants). The overall R^2 was .50, $F(1, 22) = 21.86$, $p < .001$; effect size (f^2) = 1.0, indicating a very strong relationship between these variables. Thus, the greater the amount of collaborative inhibition at either Recall 2 or Recall 3 (but particularly in Recall 3, where the variable accounts for 50%

of the variance among subjects), the greater the amount of retrieval disruption of idiosyncratic organization, and thus the more shared memories that form during final individual recall. We can consider the above evidence to be stronger than mere correlation because of the time course of the recall sessions. The final individual recall session, where shared memory formation is assessed, occurs after collaboration for all participants. Thus, even though correlational analyses in general cannot indicate causality among these two variables, the time course allows us to directionally speculate that it is most likely collaboration itself (happening during Recall 2 or Recall 3), which leads to greater shared memory formation downstream on Recall 4.

The Influence of Collaboration on Retrieval Structure: Shared Organization

Next, we wanted to examine the influence of collaboration on the development of a shared organization across participants and to assess whether this similarity in organization arose because participants were adopting the organization of the collaborative group. To examine this possibility, as noted in the introduction, we constructed a measure that was novel to this particular study: the Shared Organizational Metric Analysis (SOMA). This analysis is essentially a variation on the paired frequency (PF) analysis (Sternberg & Tulving, 1977), as can be seen in the Appendix. PF is designed to examine the degree to which items recalled in adjacent output positions during an initial recall are also recalled together on a follow-up recall. Thus, the PF measure is a within-subject analysis. The variation used in the present study is essentially a "horizontal" (i.e., between-subjects) PF. This analysis examines the recall output positions *across* two participants in order to determine whether shared memory items are in adjacent output positions (forward or backward) in the recall of both participants.[7]

Thus, we examined the influence of the various retrieval sequences on the formation of shared organization (SOMA). To assess baseline levels of shared organization (SOMA), a one-way between-subjects ANOVA was conducted with group as the factor. There were no differences in baseline levels of SOMA across conditions, $F(3, 140) = 0.32$, $MSE = 2.10$, $p = .81$, $d = .09$.

In order to perform shared organization analyses in a parallel way to how we performed the shared memory analyses, we nonetheless controlled for baseline levels of shared organization by conducting an ANCOVA in which the dependent variable was shared organization (SOMA) at Recall 4, the independent variable was group, and the covariate was shared organization (SOMA) at Recall 1. Prior to conducting the ANCOVA, examination of the assumption of homogeneity of regression determined that the interaction between the covariate and the independent variable was small (increment in $R^2 = .005$) and was not significant ($F < 1$). The ANCOVA yielded a significant difference among the four conditions, $F(3, 139) = 21.91$, $MSE = 6.99$, $p < .001$; effect size (partial η^2) = .321. Adjusted means and standard errors for the four conditions are shown in Figure 2. Follow-up pairwise comparisons indicated that participants in Early Collaboration ($M = 6.21$, $p < .001$, $d = 1.22$), Late Collaboration ($M = 5.29$, $p < .002$, $d = .88$), and Multiple Collaboration ($M = 7.91$, $p < .001$, $d = 1.86$) conditions all demonstrated a significantly greater shared organization among participants on their final individual recall compared with those participants in the control condition ($M = 2.97$), in which SOMA was measured across three individuals who never collaborated (i.e., in the form of nominal groups). In addition, Multiple Collaboration produced significantly better shared organization than both Early ($p = .04$, $d = .64$) and Late Collaboration ($p < .001$, $d = .99$) conditions, whereas the latter two did not differ ($p = .87$, $d = .35$).

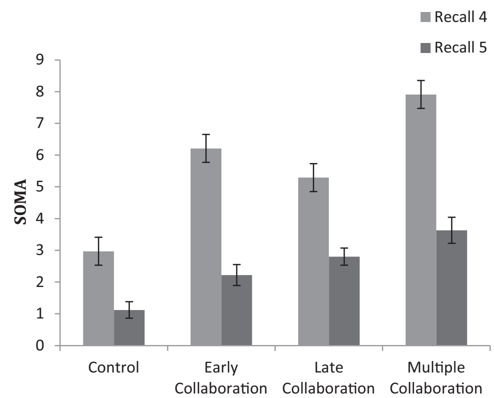

Figure 2. Shared organization at Recall 4 (immediate) and Recall 5 (after 1-week delay). SOMA = Shared Organizational Metric Analysis. Error bars represent standard errors.

Next, in order to investigate the influence of group on shared organization persistence across delay (Recall 5), a one-way between-subjects ANOVA was conducted with group as the factor. Means and standard errors for the shared organization measure across the four conditions are shown in Figure 2. There was a significant main effect of group, $F(3, 140) = 10.70$, $MSE = 3.74$, $p < .001$, $d = .91$, and follow-up pairwise comparisons showed that Multiple Collaboration participants ($M = 3.63$) maintained a significantly higher level of shared organization compared with control participants ($M = 1.12$, $p < .001$, $d = 1.22$), as well as compared with Early Collaboration participants ($M = 2.22$, $p = .01$, $d = .63$). In addition, Late Collaboration participants ($M = 2.80$) maintained higher levels of shared organization compared with control participants ($p = .002$, $d = 1.06$). However, the difference between the amounts of shared organizational persistence failed to reach statistical significance for comparisons between control and Early Collaboration participants ($p = .10$, $d = .62$), Early and Late Collaboration participants ($p = 1.00$, $d = .32$), or between Late and Multiple Collaboration participants ($p = .43$, $d = .40$).

The Modulating Effect of Collaborative Inhibition on the Formation of Shared Organization

As with the shared memory data presented earlier, we next wanted to examine whether the finding that collaboration influences the amount of shared organization is dependent on the size of the collaborative inhibition effect. Again, if this turned out to be

[7] As the original PF measure contains no upper-bound on the size of the effect, the SOMA measure also contains no upper-bound. The measure is primarily used as a comparative measure across conditions, as is the published measure of PF from which SOMA is derived.

the case, these results would demonstrate that the more people experience a disruption of their own idiosyncratic manner of organizing the past, the more likely they are to share similar structures in their memory following collaboration (in addition to the similar content that our earlier results demonstrate). To examine this possibility, we conducted a series of regression analyses examining the relationship between the size of the collaborative inhibition effect and the amount of shared organization that develops afterwards.

First, we conducted a regression analysis in which the amount of shared organization formed during Recall 4 was the criterion variable and the size of the collaborative inhibition effect at Recall 2 was the predictor variable (for the Early and Multiple Collaboration participants). The overall R^2 was .25, $F(1, 22) = 7.51$, $p = .012$; effect size $(f^2) = .33$, indicating a strong relationship between these two variables. Likewise, another regression analysis was conducted with the amount of shared organization formed during Recall 4 as the criterion variable and the size of the collaborative inhibition effect at Recall 3 serving as the predictor (for the Late and Multiple Collaboration participants). The overall R^2 was .43, $F(1, 22) = 16.52$, $p = .001$; effect size $(f^2) = .75$, indicating a very strong relationship between these variables. Thus, the greater the amount of collaborative inhibition at either Recall 2 or Recall 3 (but particularly in Recall 3, where the variable accounts for 43% of the variance among subjects), the greater the amount of retrieval disruption of idiosyncratic organization, and thus the more shared organization that forms during final individual recall. Once again, we can consider the above evidence to be stronger than mere correlation because of the time course of the recall sessions.

The Modulating Effect of Collaborative Inhibition on the Organizational Structure of Final Individual Recall: The Origin Analysis

We next wanted to examine how collaboration may change people's reliance on their original, idiosyncratic method of structuring their recall that they had produced prior to collaborating with others to remember the past (i.e., Recall 1). Specifically, we wanted to examine the degree of organizational overlap between people's final individual memory (Recall 4) and their pre-collaborative, individual memory (Recall 1). This question is important to assess, as participants may be structuring their final individual recall in similar ways to the organizational structure of any of the previous retrieval sessions in which they have engaged, or they may create an entirely new organization during this final recall. We assessed this overlap in two ways: one, by calculating traditional PF scores and, two, by conducting the novel Origin Analysis. For the PF measure, we performed a one-way between-subjects ANOVA with group condition as the factor to determine the influence of collaboration on the degree to which participants were able to reproduce their original way of structuring their memories. Results indicated there were no significant differences across the four conditions (Control: $M = 6.02$; Early Collaboration: $M = 5.84$; Late Collaboration: $M = 5.27$; Multiple Collaboration: $M = 5.02$) in terms of the degree to which the participants' final individual recall (Recall 4) overlapped structurally with their precollaborative, individual recall (Recall 1), $F(3, 140) = 0.76$, $MSE = 10.56$, $p = .52$; effect size (partial η^2) = .02. However, as will be seen below in the Origin Analysis, there were differences in the degree to which participants in the Early and Late Collaboration conditions relied on the organization of the group in which they had previously collaborated. In other words, although the PF measure was not sensitive enough to detect the changes that occurred from Recall 1 to Recall 4, the finer-grained Origin Analysis detected the influence of intervening collaboration.

The Origin Analysis has important implications for understanding how previous retrievals influence a person's current recall of the past. It is known that memory cues typically do not activate single episodes from the past but parts of multiple episodes, what Neisser termed "repisodes" (Neisser, 1981). In addition, the act of reactivating a particular memory trace itself causes another trace to be put down into long-term memory (Logan, 1988). After a while, people may come to reactivate the "memories of remembering" more so than the original memory itself (Lindsay, 2008). In essence, if one's recall is composed of clusters from multiple previous retrievals, we can assume that the participant is actually accessing at least part of each previous representation. Thus, given that the act of retrieval activates parts of representations from many previous retrieval opportunities, it makes sense that they would be activating not only the information contained within each repisode but also *the organized manner* in which the information was recalled. We examined these ideas quantitatively to assess the degree to which a participant's current recall and organization were dependent on the organization of previous recalls by creating the Origin Analysis. This analysis allows for the identification of the fingerprints or markers of individual and group influences on post-collaborative recall, where it is used to determine where each cluster originated. Specifically, we identified the clusters of items participants recalled together post-collaboratively (on Recall 4), selected specific items within each cluster, and then looked to both the pre-collaborative individual recall and collaborative recall sessions to determine what items surrounded each selected item at those times.

If a person's current retrieval organization in a recall session is dependent on and forms as a result of the organization seen in retrievals further back in time than just the immediately preceding retrieval, we classify it as being Hyperdependent. Thus, to say that a person's retrieval is "hyperdependent" means that it is dependent on more than just the preceding retrieval. This situation is in contrast to one in which a person's current recall is dependent on the retrieval organization of primarily the immediately preceding retrieval, a situation termed Dependent recall.

To determine the dependency of Recall 4 upon previous recalls, we coded all of the items produced by a participant during Recall 4 according to three variables: "orphan items," which are those items that do not form part of a cluster at all (i.e., they are items that are not recalled in adjacent output positions with other items from the same taxonomic category), "newborn clusters," which are clusters of items from the same taxonomic category that did not previously appear on either participants' Recall 2 or Recall 3, and "synergistic clusters," which are those clusters of items from the same taxonomic category where the items did co-occur together on previous recalls. These latter clusters were named after Tulving's idea of *synergistic ecphory*, a phenomenon whereby any mental process in which an individual is currently engaged (such as retrieval of information) that is similar to a past process in which the individual engaged (such as a previous retrieval of the same information) can cue the reactivation of that past process (perhaps in the same manner in which that same reactivated information had been organized during the previous retrieval; Tulving, 1984). These synergistic clusters were then assessed to determine whether they appeared only during Recall 2, only during Recall 3, if they appeared on both Recalls 2 and 3, or if they were actually composed of a hybrid of clusters that appeared at different time points. For the sake of including only those variables that are informative to this study and are significant, we do not discuss hybrid synergistic clusters, orphan items, or newborn clusters. Only synergistic clusters that appeared solely on Recall 2 or Recall 3 are discussed.

A one-way between-subjects ANOVA determined that Late Collaboration participants produced more synergistic clusters ($M = .30$) in their later individual recall (at Recall 4) that could be uniquely traced back to their earlier collaborative session compared with Early Collaboration participants ($M = .18$), $F(1, 70) = 12.57$, $MSE = .02$, $p = .001$, $d = .84$. In contrast, another one-way between-subjects ANOVA determined that there was no difference in the degree to which Late Collaboration participants ($M = .33$) and Early Collaboration participants ($M = .36$) produced synergistic clusters in their later individual recall (Recall 4) that could be uniquely traced back to their earlier individual session (Recall 2 for Late Collaboration and Recall 3 for Early Collaboration), $F(1, 70) = 1.33$, $MSE = .02$, $p = .25$, $d = .27$.

Follow-up analyses indicated that for the Early Collaboration participants, the synergistic clusters produced on their Recall 4 were more likely to come from their earlier individual session (their Recall 3; $M = .36$) compared with their earlier collaborative session (their Recall 2; $M = .18$), $t(35) = -5.58$, $p = .001$, $d = 1.86$. These results indicate that the Early Collaboration participants displayed a pattern of dependency, with their final individual recall (Recall 4) being dependent primarily on their immediately preceding recall. However, follow-up analyses indicated that for the Late Collaboration participants, the synergistic clusters produced on their Recall 4 were equally likely to come from both their earlier individual session (their Recall 2; $M = .33$) and their earlier collaborative session (their Recall 3; $M = .30$), $t(35) = -.49$, $p = .63$, $d = .16$. These results indicate that the Late Collaboration participants displayed a pattern of both dependency and hyperdependency, with their final individual recall (Recall 4) being dependent on both their immediately preceding recall and even earlier recall sessions. In other words, it appears that Early Collaboration participants did not access their earlier collaborative recall session to the same degree as did the Late Collaboration participants.

When combining the results of the PF analysis and the Origin Analysis together, the findings show that a participant's earliest recall within a series of retrievals had the least influence on their final memory (Recall 4), whereas the recall that occurred most recently (whether it was individual or collaborative) exerted the greatest influence. In the case of the Late Collaboration condition, we saw that both the most recent recall (Recall 3) and the recall prior to that (Recall 2) exerted influence. This most likely occurred because participants had an opportunity to reproduce their Recall 1 retrieval organizational structure during Recall 2 (which was an individual recall session), and thus consolidated that recall structure to a greater extent than did participants in the Early Collaboration condition, who did not have this opportunity and were required to collaboratively recall with others after having produced their individual retrieval organizational structure only once. In other words, participants in the Early Collaboration condition had unstable retrieval organization during Recall 2 and Recall 3 and thus could not take advantage of preceding retrieval organizational structure beyond the most recent recall (Recall 3), whereas those in the Late Collaboration condition had a relatively more consolidated retrieval organization in Recall 2, enabling them to take advantage of retrieval organizational structures from both the most recent (Recall 3) and the preceding (Recall 2) opportunities. Thus, it appears that the extent to which any preceding recall has an influence on one's final recall depends on the recency of the recall and whether it contains a consolidated organizational structure (i.e., a structure that has been produced more than once across previous retrievals).[8]

General Discussion

Recent studies show that the act of collaborative recall in a group influences people's post-collaborative individual memory. Less is known, however, about how groups of people collaborating together create and maintain shared memories of the past. We took a novel approach to the study of such shared memory by examining whether the process of collaboration induces people to reorganize their later individual recall, particularly by organizing their memories according to the way the group organized their recall during collaboration. We then examined how, as a result of such reorganization, people may come to develop not only similar content about the past but also similar ways of organizing that content.

We focused on examining the influence of both the frequency and timing of collaboration by comparing participants who collaborated early in a series of recalls (Early Collaboration), late in a series of recalls (Late Collaboration), multiple times within a series of recalls (Multiple Collaboration), and those who worked by themselves throughout the series of recalls (Control). We were specifically interested in how the frequency and timing of collaboration affected participants' organization, and how this in turn influenced the formation of shared memory content, its structure, and its persistence over time. Across numerous foundational and novel analyses, we found that shared memory was strongly tied to the amount of shared organization that developed among participants, as well as to the size of the collaborative inhibition effect that occurred during collaborative recall.

When viewed as a whole, the analyses presented in this study provide a conceptual triangulation of the influence that collaborating with others to recall the past has on our own individual memory. We can first start by drawing on the extensive research literature investigating collaborative inhibition. We know that

[8] We addressed these issues not just with the Origin Analysis, but also by looking at the overlap with retrieval structures using the traditional PF analysis (Sternberg & Tulving, 1977). The results of the PF analyses converged on the same conclusion, indicating that the greater the size of the collaborative inhibition effect, the greater the degree of overlap between the retrieval organization of the Early and Late Collaboration participants' final individual recall (Recall 4) and the group organization formed during their earlier collaborative session (either Recall 2 or Recall 3). In other words, this indicates a greater adoption of the organizational structure formed by the group during collaboration by participants on their final individual recall.

when people work together with others to remember the past, they are likely to disrupt each other's idiosyncratic way of having organized their memories as they were learning them (and as they had originally produced them during earlier individual recall sessions). The more disruption people experience during collaboration, the greater the size of the collaborative inhibition effect. The results of the present study indicate that the greater the size of the collaborative inhibition effect, the more likely participants are to adopt the organization formed during the collaborative session itself in their later individual recall (Recall 4) compared with recreating their own pre-collaborative, individual recall (Recall 1). As all the former collaborators are likely to rely on this group organization (and thus reproduce the output contained within that organizational structure), they consequently have greater overlap in both the content and structure of their later individual recall compared with participants who never collaborated. Supporting this idea is the finding of positive associations between the size of the collaborative inhibition effect and the development of both shared memory and shared organization.

The results also indicated that collaborating at any time during the series of recalls (i.e., whether early or late) led to a greater amount of shared memory and shared organization compared with those who never collaborated. In addition, those participants who collaborated multiple times showed the greatest shared memory and shared organizational formation. Collaborative recall showed a similar influence on the persistence of shared memory. Both shared memory and shared organization remained higher after a 1-week delay for participants who previously collaborated compared with those who never collaborated, and the highest for those who collaborated multiple times.

The overlap in the content and organization of memories that developed among collaborators suggests that these individuals incorporated items that were recalled during collaboration, as well as the sequence in which these items were recalled, into their final individual recall. We examined this possibility by conducting the Origin Analysis. In later individual recall (Recall 4), the synergistic clusters of items (i.e., those that co-occurred together in previous recalls) produced by the Late Collaboration participants were equally likely to come from either their earlier individual or collaborative recall sessions, but the Early Collaboration participants relied more on the organization from their immediately preceding individual session. The Early and Late collaboration patterns show that clusters from individual recall—whether they occurred early or late—remain evident in later individual recall. But clusters formed during collaborative recall persist in later individual recall only when collaboration occurred recently, as is seen in the Late Collaboration condition. These findings suggest that individually formed clusters are more enduring than the clusters formed during collaboration, and makes sense in light of the idiosyncratic cognitive structures of individuals that have coalesced over a long time. However, we might expect to see a different pattern of results if our participants had been close intimates (e.g., long-time friends or couples) rather than strangers, who would be used to recalling information multiple times with their partner over the span of their relationship. In such situations, it is likely that the shared organizational structure that had developed between the intimates might be more enduring than the idiosyncratic structure that each person possesses.[9]

The weak influence of early collaborative recall on later individual memory structure also explains why early collaborative recall is ineffective for the persistence of shared memory over a 1-week delay. It was found that across the 1-week delay, Early Collaboration participants showed poorer shared memory and shared organization in recall compared with participants in the Late and Multiple Collaboration conditions. There was also no difference in the extent to which Early Collaboration participants retained their shared organization levels in comparison to participants in the control condition, whereas both Late and Multiple Collaboration participants showed greater shared organization compared with the Early Collaboration participants. These findings suggest that the participants who collaborated early were unable to access their earlier collaborative session to the same extent as those who collaborated later in the recall sequence.

This influence of collaboration on individual memory is impressive, and, in this context, our study points to a boundary condition for this effect: If collaboration occurs too early in the process of retrieval, its relation to later recall is diminished. In other words, not all collaborations are the same. Both the frequency and timing of collaboration matter for the way this process shapes shared memory representations.

Theoretical Implications

Here we discuss three key implications of our findings, namely, for the architecture of shared representations, for collective memory research, and for other areas of psychological research. With respect to the architecture of shared representations, we posit here that shared representations may include more than just overlapping or shared memories across individuals. For instance, enduring shared representations also include the alignment of the organization of the memory itself in such a way that all participants who share that memory possess similar cues needed to reconstruct the representation. In the absence of such organization, which is a key variable involved in the persistence of individual and group memory across time (e.g., Mulligan, 2005; Puff, 1979; Tulving, 1972), a shared representation may only exist during the specific temporal point at which collaborative discussion occurred but may dissipate over time.

One potential consequence of the organizational alignment of participants' post-collaborative memory is a reduction in their ability to use targeted retrieval cues to access non-shared information that existed prior to collaborative discussion, known as *reduced cue specificity* (Andersson & Ronnberg, 1997). At the same time, the act of collaboration does lead to increased *shared cue specificity* among former collaborators for the content retrieved during collaboration. As a result, whenever a former collaborator uses a shared cue, they access a shared representation that their fellow collaborators are also able to access. This concept is similar to one proposed by Vygotsky (1978), who claimed that individual psychological functions are the instantiations of the psychological interactions between people engaged in activity in the external social world. On the basis of our results, one could argue that organization itself is the manifestation of the instantiation of these interactions within an individual, an idea that has implications for developmental psychologists interested in parent–child conversations (discussed below).

[9] We thank an anonymous reviewer for clarifying this idea.

Implications for collective memory research. Though our study focused on understanding the process by which shared memories form, our results can speak to an important aspect of collective memory formation as well, specifically what is known as "collective remembering." Wertsch & Roediger (2008) argued that collective remembering can be conceptualized as more of a reconstructive process (e.g., Bartlett, 1932) rather than the retrieval or reactivation of a shared body of knowledge (such as in the form of an engram; e.g., Semon, 1904; Tulving, 1983). However, this reconstructive process specifically occurs in the context of social and political situations (such as within family discussions or history textbooks). As such, collective remembering on some level may represent a narrative reconstruction of a "national identity," which may be compared with how an individual's episodic or autobiographical memory may be conceptualized as a narrative that organizes information into a cohesive representation about a past experience (e.g., Conway & Pleydell-Pearce, 2000). Whereas narrative forms of individual memory are assumed to be produced, organized, and constrained by the cognitive faculties of an individual person, national narratives are assumed to be shared across adherents of a particular group and constrained by the "cultural tools" available, such as narrative forms (Wertsch & Roediger, 2008). Although cultural tools may provide a top-down constraint on what information people discuss within the cultural context (or an organizational scheme used to classify information), our findings indicate that the process of collaboration may instantiate a cognitively based, bottom-up accumulation of shared representations among former collaborators that may act as mini cultural tools they use to access shared representations. For example, members of a small community within a larger culture may have collaborative discussions with one another and thereby develop shared cues that can be used to access shared representations formed within that particular community. As such, collaborative discussions may be acting as one of the mechanisms by which variation within a larger, culturally prescribed national narrative emerges. Thus, our study identifies the cognitive constituent processes that underlie the formation and persistence of shared memories and specifies a microlevel of analysis to provide a more layered understanding of within-culture differences that underlie collective memory formation and persistence on a large scale.

Broader research implications. The results of this study have many widespread research implications across a range of domains in psychological research. For example, the organizational alignment caused by collaboration will likely influence not only participants' memories, but presumably downstream cognitive activities that are known to be affected by memory, including the formation of beliefs and attitudes (Wyer & Albarracin, 2005). Specifically, research on belief and attitude formation has demonstrated that one of the most important factors involved in the process is what knowledge is accessible at the time of evaluation. Our results indicate that knowledge accessibility can be influenced by the collaborative process through the alignment of a collaborator's individual organization with the group-level organization that emerges during the collaborative discussion itself. As all former collaborators are likely to draw on similar stores of accessible knowledge when making evaluations, they are likely to subsequently form similar beliefs.

Another testable prediction derived from our results relates to the consequences of any particular collaboration on future collaborative discussions. Specifically, it is likely that when groups form a shared representation of the material, future collaboration among those same group members could lead to the perpetuation of information that is already collectively held. For example, research has shown that groups tend to accentuate the widely shared biases of the individuals within those groups, as well as to attenuate uncommon biases when shared representations are strong (Betts & Hinsz, 2013). Thus, one could speculate that one of the potential reasons in which stereotypes and other culturally shared biases are maintained among like-minded individuals is the alignment and maintenance of their individual representations of the information through repeated collaborative encounters with other like-minded individuals, a hypothesis we are currently testing in empirical research.

In addition, our results have implications for developmental psychologists who study parent–child conversations and the role they play in the development of a child's autobiographical memory (e.g., Nelson & Fivush, 2004; Wang & Fivush, 2005). Specifically, autobiographical memory is said to develop when children align their way of organizing their autobiographical experience to the model or structure used by their parents. Children eventually internalize that narrative model and subsequently use it to learn, organize, and retrieve their autobiographical memories in a coherent fashion in the future. The results of our study, especially the findings on the persistence of shared memory organization, intimate that such alignment may lead to children developing and maintaining shared narrative representations with their parents even in the absence of additional parent–child conversations. It is then reasonable to further speculate that children would continue to structure any new autobiographical experience they encounter using the model they internalized from their parents.

Our results also have intriguing educational implications. The learning of any specialized discipline typically involves students acquiring information in a structured format by first learning foundational principles and then building on those principles in an organized fashion. Indeed, some specialized information is actually imparted to students in organized clusters, such as biological classification schemes (i.e., family, species, etc.), principles of physics, or mathematical equations. On the basis of the results of this study, it seems highly probable that students taught in such structured formats, especially those who are taught with cooperative learning methods and encouraged to work with others to learn (e.g., Johnson, Johnson, & Stanne, 2000), will develop shared representations of the material, particularly among those students who are taught in the same classroom by the same teacher and using the same textbook. Indeed, such an outcome may be the primary goal of learning highly specialized or esoteric knowledge. However, the results of this study provide intriguing implications for the consequences of the development of such shared representations. For example, if all students share a similar way of organizing the information within a discipline, they may base many important decisions, including the construction of scientific hypotheses, upon the content of knowledge contained within those representations. As the instantiation of similar representations may discourage individuals from having idiosyncratic ways of organizing and engaging with the material, the presence of shared organization may actually limit innovative ways of approaching problems addressed by the material. It would be interesting to examine whether one marker of creativity might be the ability to organize specialized material in ways contrary to the commonly available organizing principles established within the particular discipline.

The results of this study demonstrate that collaboration provides one method by which shared representations may be formed precisely because of the effect it has on organization. This relationship can illuminate why certain real-world settings might accelerate the development of shared organization (i.e., educational settings, and particularly those that use cooperative learning techniques that require students to engage in classroom activities that focus on shared learning goals, as was mentioned above; Johnson, Johnson, & Stanne, 2000). For example, schools may use a single textbook across multiple school districts, creating a situation in which students are not only studying the same material but also learning it in the exact same organized format. Such a situation provides a ready-made, group-level organization of the material that each student likely retains when their school course is completed. In other words, a shared representation may develop. As this situation likely occurs across multiple areas within a country, it has important implications for the study of collective memories and their relation to group identity (Hirst & Manier, 2008), including how learning the history of one's culture from textbooks may contribute to the development of collective memories (e.g., Roediger, Zaromb, & Butler, 2009).

Finally, implications also emerge from our results regarding work on the nature of categorization and the development of culturally shared concepts. Bruner (1957) argued that people organize information into hierarchical arrangements of related categories (or taxonomies) and that there is continuity between perceptual and conceptual categorization, that is, between how people categorize sensory stimuli as well as the cognitive operations they perform mentally on the stimuli. He stated that ". . . adequate perceptual representation involves the learning of appropriate categories, the learning of cues useful in placing objects appropriately in such systems of categories, and the learning of what objects are likely to occur in the environment" (Bruner, 1957, p. 127). This idea is similar to work by Emile Durkheim, who argued that early belief systems arose from the human tendency to classify nature into categories (Durkheim, 1915). The importance of these ideas is due to the fact that conceptual categorization can essentially be considered a necessary antecedent to memory organization, as it has been shown that people tend to impose their own subjective organization upon newly encountered information in such a way that they align the material to match the internal conceptual structure of information already contained within their long-term memory (e.g., Luhmann, Congleton, Zhao, & Rajaram, 2014; Tulving, 1972). Here, we show that interpersonal factors in the form of simple collaborative discussions can lead to an alignment of categorization strategies across individuals, a finding that has widespread implications for how groups may come to develop similar ways of viewing the world (similar to the cognitive philosophical idea of *weltanschauung*; Apostel & Van der Veken, 1991), and that may bias how they subsequently perceive new sensory information in a way that leads to a socially constructed and socially shared version of reality (Hardin & Higgins, 1996).

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(*Appendix follows*)

Appendix

Calculation of Shared Organizational Metric Analysis (SOMA)

Paired Frequency (Sternberg & Tulving, 1977)

- **PF**: O(ITR2) – E(ITR2) = O(ITR2) – 2c(c-1)/hk
  - O(ITR2) = the number of pairs of items recalled on Trials t and t+1 in adjacent output positions in either of two possible orders (forward or backward pairs)
  - E(ITR2) = the expected number of pairs of items
  - c = the number of common items recalled on both Trials t and t+1
  - h = the number of items recalled on Trial t
  - k = the number of items recalled on Trial t+1

Shared Organizational Metric Analysis (SOMA)

- **SOMA**: O(ITR2) – E(ITR2) = O(ITR2) – 2c(c-1)/hk
  - O(ITR2) = the number of pairs of items recalled by Person A and Person B in adjacent output positions in either of two possible orders (forward or backward pairs)
  - E(ITR2) = the expected number of pairs of items
  - c = the number of common items recalled by Person A and Person B
  - h = the number of items recalled by Person A
  - k = the number of items recalled by Person B

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