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Collaborative inhibition in spatial memory retrieval

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Abstract *Collaborative inhibition* refers to the finding that pairs of people working together to retrieve information from memory—a collaborative group—often retrieve fewer unique items than do nominal pairs, who retrieve individually but whose performance is pooled. Two experiments were designed to explore whether collaborative inhibition, which has heretofore been studied using traditional memory stimuli such as word lists, also characterizes spatial memory retrieval. In the present study, participants learned a layout of objects and then reconstructed the layout from memory, either individually or in pairs. The layouts created by collaborative pairs were more accurate than those created by individuals, but less accurate than those of nominal pairs, providing evidence for collaborative inhibition in spatial memory retrieval. Collaborative inhibition occurred when participants were allowed to dictate the order of object placement during reconstruction (Exp. 1), and also when object order was imposed by the experimenter (Exp. 2), which was intended to disrupt the retrieval processes of pairs as well as of individuals. Individual tests of perspective taking indicated that the underlying representations of pair members were no different than those of individuals; in all cases, spatial memories were organized around a reference frame aligned with the studied perspective. These results suggest that inhibition is caused by the product of group recall (i.e., seeing a partner's object placement), not by the process of group recall (i.e., taking turns choosing an object to place). The present study has implications for how group performance on a collaborative spatial memory task may be optimized.

Keywords Collaborative inhibition · Spatial cognition · Memory · Reference frames

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People often work together to solve problems as a group. For instance, conducting a research study and writing a paper are common collaborative tasks undertaken by multiple individuals. Because collaborative work is so common, it is important to understand the effects of collaboration on memory and group performance. It may be expected that group performance on a memory task, for instance, would be equal to, or even greater than, the sum of the individual performances of each group member. That is, it seems logical that the group would have access to all of the information that each group member could recall as an individual, therefore leading to enhanced group performance. However, this is not always the case.

When a collaborative group's performance on a memory task is compared to a single individual's performance, the collaborative group typically performs better (e.g., recalls more items), on average, than does the individual. This result is not surprising, since a group of people will be able to remember more collectively than a single person can. However, nominal groups formed by combining the responses of individuals in a nonredundant fashion will often outperform the collaborative group (for reviews, see Rajaram, 2011; Rajaram & Pereira-Pasarin, 2010), a finding referred to as *collaborative inhibition* (Blumen & Rajaram, 2008; Weldon & Bellinger, 1997). The majority of existing research on collaborative inhibition has examined the retrieval of simple word lists. One goal of the present project was to examine whether collaborative inhibition occurs in a more complex spatial memory task, in which participants learn the locations of objects in a room. A second goal of the present project was to clarify the underlying cause of collaborative inhibition.

The exact cause of collaborative inhibition is a topic of ongoing research, but it is generally considered to be caused by disruption of memory retrieval (Weldon, Blair, & Huebsch, 2000). Retrieval disruption might occur through multiple mechanisms, including process-based disruption (Basden,

Basden, Bryner, & Thomas, 1997) and product-based disruption (Wright & Klumpp, 2004). *Process-based* disruption occurs when one person's retrieval strategy interferes with another person's retrieval strategy, thereby reducing the overall amount of information they will collectively recall. An example of process-based disruption is the negative effect of group turn-taking, whereby an individual's retrieval strategy is continually interrupted by the responses of other group members. Evidence for such process disruption is that collaborative pairs perform no worse than nominal pairs when recall is cued (Finlay, Hitch, & Meudell, 2000) or when a particular recall strategy is enforced (Basden et al., 1997), both of which serve to disrupt the retrieval processes of individuals and groups alike. *Product-based* disruption could occur when the recalled items themselves interfere with an individual's recall of additional items. For example, if one individual of a collaborative pair recalls a word from the end of the list, that word could prime neighboring words in his or her partner's memory, at the expense of words that were at the beginning of the list. This explanation is similar to the effects of part-list cueing, whereby exposure to a subset of to-be-remembered items interferes with subsequent recall of the remaining items (see Nickerson, 1984, for a review). Furthermore, false recollection of words that were not on the studied list could distract a collaborative partner. In these examples, the group-recalled items themselves could interfere with the retrieval of other items. Evidence for such product-based disruption has come from research showing that collaborative pairs recall just as many word list items as nominal pairs when they take turns recalling but are not allowed to see their partner's responses (Wright & Klumpp, 2004).

Collaborative inhibition has been found in a variety of memory tasks. The most widely used task for studying collaborative inhibition is list recall (Basden et al., 1997; Finlay et al., 2000; Thorley & Dewhurst, 2007), but collaborative effects have also been found in recall for prose (Weldon & Bellinger, 1997), pictures (Finlay et al., 2000), and videos (Andersson & Rönnberg, 1995; Ekeocha & Brennan, 2008).

One type of learning that has received little attention in the collaborative-learning literature is spatial learning. Spatial memory reconstruction is often a collaborative task. For instance, when multiple people in an unfamiliar city attempt to walk together from a hotel to a restaurant, the group often works together to determine the best route. Such a collaborative task requires multiple individuals to retrieve imperfect spatial knowledge of the neighborhood and come to an agreement about the spatial layout. This collaboration may result in collaborative inhibition, because the collaborative group may remember the city's layout less accurately than they would if each individual recalled the city layout separately and their memories were pooled after recall (thus forming a nominal group).

Spatial memories are thought to be organized around reference frames, and existing research on collaborative spatial tasks has typically focused on this reference frame organization. Imagining different perspectives in a remembered environment, as one might do when planning a route through a known neighborhood, often reveals a small number of preferred perspectives in memory that are easier to imagine than other perspectives, and this facilitation pattern is believed to reflect the reference frame structure of spatial memory. Perspectives aligned with the reference frame are directly represented in memory, whereas misaligned perspectives must be imagined through transformation of the spatial memory, and the transformation process results in increased latency and error (Klatzky, 1998). After learning a spatial layout, reference frames are often measured using judgments of relative direction (JRDs), in which participants imagine standing at one object, facing a second object and, from that imagined perspective, point to the location of a third object. By analyzing the pattern of performance across imagined perspectives, pointing performance on JRDs can be used to determine the reference frame that a given spatial memory is organized around. Reference frame selection has been found to be influenced by an interaction between egocentric experience (i.e., the studied perspectives) and environmental structures such as room axes (Kelly & McNamara, 2008; Kelly, Sjolund, & Sturz, 2013; Shelton & McNamara, 2001), buildings and streets (Marchette, Yerramsetti, Burns, & Shelton, 2011; Montello, 1991; Werner & Schmidt, 1999), sloped terrain (Kelly, 2011), and intrinsic properties of the spatial layout itself (Mou & McNamara, 2002; but see Greenauer & Waller, 2008; Richard & Waller, 2013).

Two studies have investigated the effects of collaboration on reference frame organization (Galati, Michael, Mello, Greenauer, & Avraamides, 2013; Shelton & McNamara, 2004). In both studies, pairs of participants worked together, with one participant (the "director") tasked with describing a layout of objects to another participant (the "matcher"), who attempted to recreate the layout from a perspective that was offset from the director's perspective. The matcher did not have visual access to the original layout (the matcher and director were separated by a barrier), and therefore relied on instructions from the director. After reconstruction, both the director and matcher individually completed JRDs in order to assess the reference frame(s) used to represent the layout. The matcher represented the layout using a reference frame aligned with his or her perspective during reconstruction, which is unsurprising, given that this was the only perspective the matcher had experienced (Shelton & McNamara, 2004). Importantly, the director also represented the matcher's perspective in memory. The effect of collaboration on the director's memory was found when the director was explicitly instructed to describe the layout from the matcher's perspective (Shelton & McNamara, 2004), and also when information about the matcher's perspective was only implicitly provided to the director (Galati et al., 2013).

In summary, past research has shown that collaboration during retrieval can cause collaborative inhibition for items such as word lists, but the effect of collaboration on spatial memory retrieval has heretofore been restricted to studying the effects of collaboration on reference frame organization. With the present study, we sought to connect spatial memory research on reference frame selection with research on collaborative inhibition during memory retrieval. In the present study, participants studied a layout of objects either alone or with a partner who was offset from their viewing position by 45º. The layout was then removed, and participants attempted to reconstruct the layout on their own (for singles) or as a collaborative pair (for pairs). Following reconstruction, participants individually completed JRDs in order to evaluate the reference frame organization of their memories for the layout. On the basis of previous findings of collaborative inhibition, it was hypothesized that collaborative pairs would outperform individuals on the reconstruction task, but that nominal pairs, created by combining the layouts of two individuals, would outperform collaborative pairs. Additionally, if the mere presence of a partner standing at another perspective is sufficient to influence reference frame selection, then it was hypothesized that JRD performance from the partner's perspective would be affected, consistent with Galati et al. (2013). However, if the expectation of subsequent collaboration is necessary for JRD performance to be affected by a partner, then we should find no effect of partner presence on JRD performance.

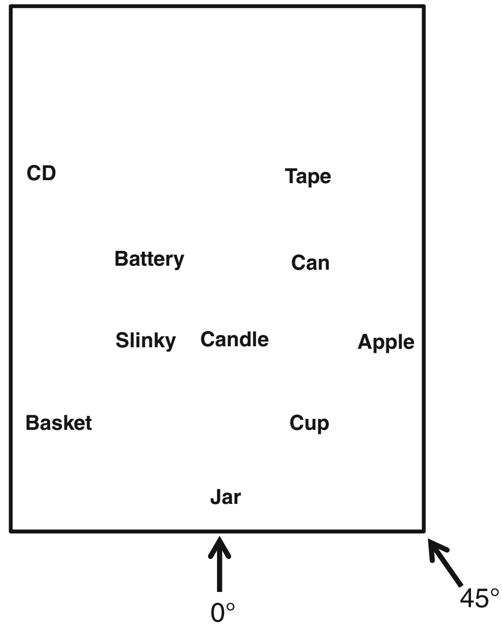

Fig. 1 Object locations used in Experiments 1 and 2. Participants studied the layout from one of two perspectives, indicated by arrows at 0º and 45º. The thin lines bordering the layout represent the edges of the rectangular rug

Experiment 1

Method

Participants A group of 64 undergraduate students from Iowa State University participated in exchange for course credit. Sixteen of the participants were assigned to each of the two individual conditions, and 32 participants were assigned to the collaborative condition.

Stimuli and design The layout consisted of ten objects arranged on a 1.52 × 2.11 m rectangular rug. The rug was placed near the corner of a 5.75 × 5.75 m room, such that the edges of the rug were parallel to the room walls and the nearest edges were 0.7 m from the wall. The layout objects included a jar, cup, Post-its, apple, candle, Slinky, pop can, battery, tape, and CD (see Fig. 1 for the layout of the objects). The layout was studied from either the 0º or 45º viewing perspective during learning.

Sixty-four JRD trials were constructed using the names of objects from the layout. Each trial appeared as a sentence on a computer monitor, instructing participants to imagine standing at one object while facing a second object, and to point to a third object from that imagined perspective (e.g., "Imagine standing at the CD, facing the battery. Point to the tape."). Pointing was accomplished by deflecting a joystick in the desired direction. The direction from the standing object to the facing object comprised the imagined perspective, which varied in 45º increments from 0º to 315º. Eight unique trials were generated for each imagined perspective, and the correct egocentric pointing direction (the pointing direction that was required to produce a correct response: 0º to 315º, in 45º increments) was counterbalanced across imagined perspectives to control for the relative ease of pointing to objects in front of the imagined perspective (Kelly & McNamara, 2009).

Participants studied the layout and later completed a layout reconstruction task, and both tasks were done either individually or in pairs (i.e., individual studying was always followed by individual reconstruction, and pair studying was always followed by pair reconstruction). All participants then completed the JRD task individually. The independent variables were viewing angle (0º or 45º) and collaborative condition (single or pair) during study/reconstruction, as well as imagined perspective on JRD trials. The dependent variable for the reconstruction task was the bidimensional correlation between the actual and reconstructed layouts. The primary dependent variable for the JRD task was absolute pointing error, and pointing latency was also recorded.

Procedure Participants were assigned to participate as a single participant or in a pair by allowing undergraduate students to voluntarily sign up for one of two concurrent timeslots. If both concurrent timeslots were filled, then those participants were run as a pair. If only one timeslot was filled, then that participant was run as a single. Participants were told that they would study a layout of objects and later be tested on their memory for the object locations. The participants in pairs were not explicitly told that they would perform the memory retrieval collaboratively until after learning, at which time both participants were informed together. All participants were blindfolded and led to either the 0º perspective or the 45º perspective (see Fig. 1 for the studied perspectives). For the single participants, the 0º perspective or the 45º perspective were randomly assigned and balanced so that equal numbers were assigned to each perspective condition. For the paired participants, one participant was randomly assigned to the 0º perspective and the other to the 45º perspective.

When the participants were in their assigned locations, they were instructed to remove their blindfolds, and the experimenter pointed to each of the objects in the layout in a random order while saying the name of the object. The participants were instructed to study the layout of objects for 20 s. After 20 s had passed, participants were instructed to replace their blindfolds and point with their hands to the remembered location of each object as the experimenter listed the objects in a random order. This study-then-point process was repeated three times, at which point all participants were able to correctly point to each object location (pointing accuracy was visually estimated by the experimenter). After reaching the learning criterion, participants were instructed to again don their blindfolds while the experimenter removed the layout objects from the rug. The experimenter placed the objects haphazardly at the back edge of the rug, where they would be visible to the participants.

After learning was completed, participants began the reconstruction task. They were asked to remove their blindfolds and were provided with laser pointers to indicate where they thought the objects had previously been located on the rug. For pairs, one member of the pair was randomly selected as the first respondent. Participants began by selecting one object from the collection of objects and indicating where on the rug that object had previously been located by pointing to the location with the laser pointer. The experimenter then placed the object in the indicated location, and confirmed with the participant that this was their intended location. The participants were allowed to adjust their response until they were satisfied. Single participants continued choosing objects and indicating their remembered location until all of the objects were placed, whereas pairs took alternating turns. For pairs, after an object was placed by one participant, the other participant was allowed to indicate whether they would like to adjust the placement of that object. This alternation continued until a location was agreed upon by both participants. Both the single and paired participants were allowed to relocate any of the objects at any time during the reconstruction process.

When the participants were satisfied with the reconstructed layout, they were again blindfolded and led to another room where they independently completed the JRD task on desktop computers. The reconstructed layout was then photographed for later analysis.

Analysis For the reconstruction task, images of reconstructed layouts were coded by recording the X and Y coordinates of each object in the image using Photoshop CS5 (Adobe, San Jose, CA). Photos were taken while holding the camera at a height of approximately 8 feet, above the approximate location of the jar. To account for projective distortion, Photoshop was used to stretch the images until the rug was rectangular in the image and the rug aspect ratio was equivalent to the actual aspect ratio of the rug. Nominal pairs were constructed by combining the data from randomly paired individuals who studied alone. Each nominal pair was composed of one participant who studied from 0º and one who studied from 45º, in order to maintain consistency with the collaborative pairs. In past work using word lists, nominal pairs were created by combining the recalled lists of individual participants, excluding repeated words (Rajaram & Pereira-Pasarin, 2010). However, the reconstruction task in the present study was quite different, in that participants were provided with the objects and asked to retrieve their spatial positions. Therefore, nominal pairs were created by selecting the most accurate X and Y coordinates for each object from the two individual-participant layouts, regardless of whether those coordinates came from a single participant or from both participants. The rationale for choosing the best X and Y coordinates separately, instead of choosing the best X–Y pair, was based on observations of collaborative pairs. When collaborative pairs disagreed about an object's location, negotiation in object placement often involved multiple dimensions of space. For example, one participant might shift an object in either the X or the Y dimension alone, because he or she remembered that the object was aligned with another object. Given this tendency for collaborative pairs to make uni- and multidimensional adjustments, we believed that allowing nominal pairs this same capacity would be most similar to the collaborative pairs.

Results

Reconstruction Figure 2 summarizes the reconstructed object locations for each object in each of the four conditions. For each object, 95 %-confidence ellipses (Batschelet, 1981) were constructed using the X and Y coordinates of each reconstructed object location. For nominal pairs, eight out of ten confidence ellipses contained the actual object location, as

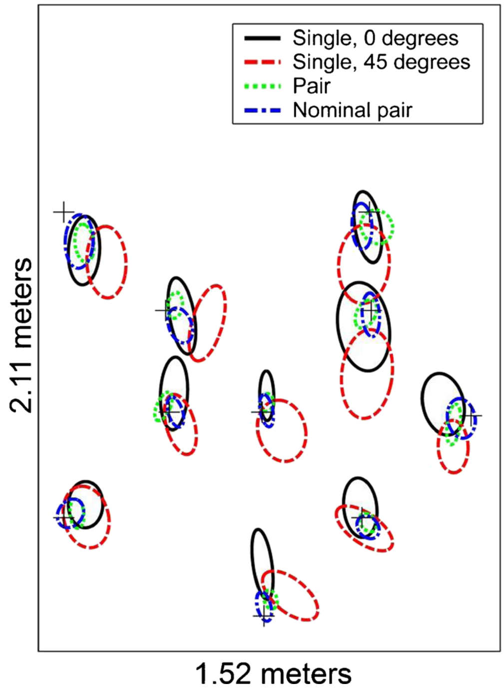

Fig. 2 Mean response locations and 95 %-confidence ellipses for the reconstructed layouts in Experiment 1. Plus symbols indicate the actual object locations, and ellipses are centered on the average response locations

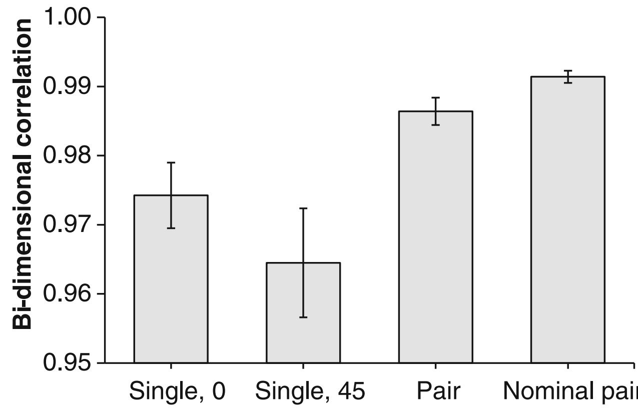

Fig. 3 Average bidimensional correlations on the layout reconstruction task in Experiment 1. Error bars indicate ±1 standard error

compared to four each for individuals from the 0º and 45º perspectives, and three for collaborative pairs. The higher number of confidence ellipses containing the actual target location in the nominal group was not due to larger confidence ellipses: Confidence ellipses were numerically smallest for the nominal pairs, followed by those of the collaborative pairs and then of individuals, although these data were not analyzed statistically.

Reconstruction accuracy was measured as the bidimensional correlations between the judged and actual object locations, which are shown in Fig. 3 as a function of learning condition. Bidimensional correlation is a measure of the similarity between two layouts while ignoring differences in layout position, orientation, and scale.[1] Due to the nature of correlations, these data represent the relative accuracy of the layout, rather than absolute accuracy (see Tobler, 1994; Waller, Loomis, & Haun, 2004). Layouts reconstructed by pairs had significantly higher bidimensional correlations than did those reconstructed by individuals who studied from the 0º perspective, $t(30) = 2.37$, $p = .025$, $d = 3.15$, or from the 45º perspective, $t(30) = 2.70$, $p = .011$, $d = 3.77$, which did not differ significantly from one another, $t(30) = 1.06$, $p = .30$. In addition, nominal pairs had significantly higher correlations than did collaborative pairs, $t(30) = 2.31$, $p = .028$, $d = 3.28$, providing evidence of collaborative inhibition.[2]

Judgments of relative direction Pointing errors were more responsive to manipulation of the independent variables than were pointing latencies. Speed–accuracy trade-offs were calculated as the correlation between errors and latencies on trials testing each of the eight imagined perspectives, separately for each participant. The average correlation across participants was .17 ($SD = .39$), which was significantly greater than zero, $t(63) = 3.35$, $p = .001$. In the interest of brevity, only pointing-error results are reported.

As can be seen in Fig. 4, two major patterns are apparent from the pointing-error data. First, absolute pointing errors were lowest when imagining the perspective aligned with the studied view. In some cases, errors were also relatively low when imagining perspectives orthogonal or opposite to the studied view. This finding is consistent with the notion that participants established a reference frame aligned with the studied view, and that spatial memory retrieval was facilitated when imagining the perspective(s) aligned with that reference frame. Second, the selected reference frame was not influenced by the presence of a partner.

These conclusions were supported by statistical analyses. Absolute pointing errors were analyzed in a mixed-model repeated measures analysis of variance (ANOVA) with terms

[1] Analyses based on absolute errors between actual and judged object locations produced identical conclusions, but are not reported here in the interest of brevity.

[2] It is possible that selecting the best X and Y coordinates inflated the performance of the nominal groups by reducing noise present in participants' representations or retrieval processes. To explore this possibility, analyses were conducted in which all of the individually reconstructed layouts were randomly perturbed (noise was sampled from a normal distribution, with a standard deviation ranging from 0 to 20 cm), creating two noisy versions of the same reconstructed layout. The two noisy layouts were combined using the nominal-pair procedure. Although a certain amount of noise did increase the bidimensional correlations of the combined layouts, the effect was small (approximately .01, at most) and did not come near the nominal-group performance.

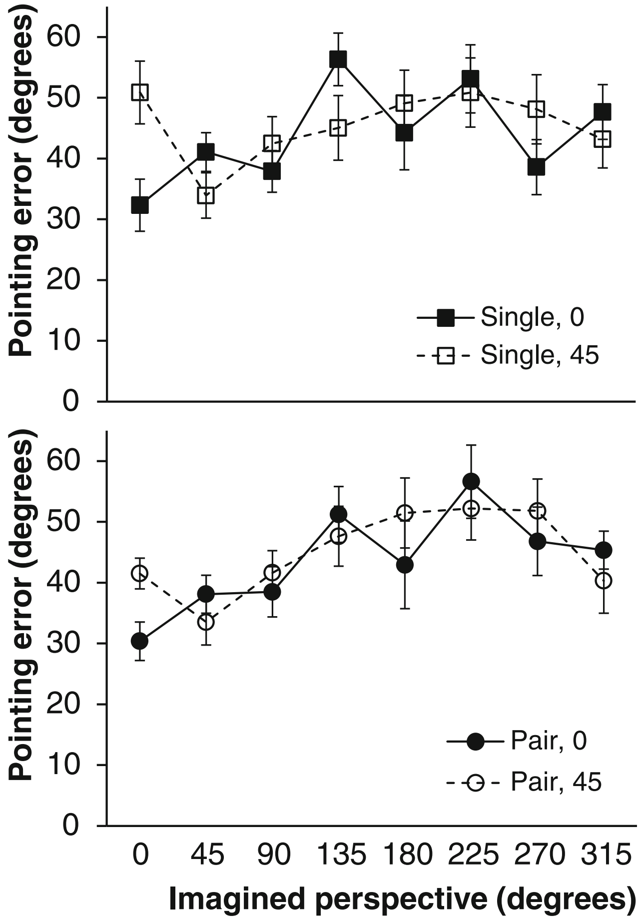

Fig. 4 Average pointing errors on the judgment-of-relative-direction task in Experiment 1, as a function of study condition (single or pair), study perspective (0º or 45º), and imagined perspective. Error bars indicate ± 1 standard error

for imagined perspective (0º–315º in increments of 45º), study view (0º or 45º), and study condition (single or pair). The main effect of imagined perspective, $F(7, 420) = 5.43$, $p < .001$, $\eta_p^2 = .08$, was qualified by an interaction between imagined perspective and study view, $F(7, 420) = 4.82$, $p < .001$, $\eta_p^2 = .07$. No other main effects or interactions were significant. The interaction contrast comparing performance on the two studied perspectives (0º and 45º) across the two viewing conditions (0º and 45º) was also significant, $F(1, 60) = 10.03$, $p = .002$, $\eta_p^2 = .14$. Analyses of participants who completed reconstruction individually indicates that JRD errors were significantly negatively correlated with bidimensional correlations on the reconstruction task $r(32) = –.41$, $p = .021$, suggesting that both measures tap into the same underlying memory.

Discussion

The results of Experiment 1 provide evidence of collaborative inhibition in a spatial memory task. The reconstructed layouts created by collaborative pairs were more accurate than the reconstructed layouts created by individuals, but less accurate than those created by nominal pairs. This complements previous research that has examined collaborative inhibition in other, vastly different tasks (Andersson & Rönnberg, 1995; Ekeocha & Brennan, 2008; Finlay et al., 2000; Weldon & Bellinger, 1997).

Additionally, JRD performance was examined for those studying alone and those studying in pairs, in order to evaluate the reference frame organization of participants' spatial memories. These data provide insights into the representations of individual participants, since JRDs were completed individually. Participants remembered the layout using a reference frame aligned with the studied view, and the presence of a partner did not significantly influence reference frame selection. At first glance, this finding appears to be at odds with the results reported by Galati et al. (2013). In the "co-presence" condition of their study, viewers spontaneously represented the viewing perspective of their partners, who were present during learning. However, participants in that condition knew that they would later be describing the layout to their partner. In the present experiment, participants were unaware that they would be collaborating on the reconstruction task and were never required or encouraged to take their partner's perspective.

These results demonstrate collaborative inhibition in spatial memory retrieval, but they do not shed light on the mechanism behind collaborative inhibition. At least two possible causes of retrieval disruption might underlie collaborative inhibition: product-based disruption (Wright & Klumpp, 2004) or process-based disruption (Basden et al., 1997; Finlay et al., 2000). In the context of Experiment 1, product-based disruption could occur if the object locations placed by one participant were incorrect or were inconsistent with the other participant's memory. For example, one participant might encode the Slinky's position relative to the battery and the candle, but errors made by his or her partner when placing the battery and the candle could disrupt the retrieval cues when placing the Slinky. Such product-based errors would impair collaborative pairs, but would not be present in nominal pairs, which do not suffer from this type of disruption. Process-based disruption could occur because the turn-taking requirement during collaborative recall could have disrupted individual participants' preferred retrieval sequences. For example, one participant might have encoded the objects in terms of their columns along the 0º–180º axis, and thus would prefer retrieval in the columnar sequence, but his or her partner might select items in an order that disrupted this preferred sequence. Such process-based disruption would impair collaborative pairs, but would not be present in nominal pairs, which do not suffer from this type of disruption.

Experiment 2 was designed to evaluate whether collaborative inhibition in spatial memory retrieval is due to the process or the product of recalling in a pair. In this experiment, neither individuals nor pairs were allowed to choose the object order during reconstruction. Instead, objects were chosen at random by the experimenter. If the process of collaborative recall is the primary source of collaborative inhibition, we should find no difference between the nominal pairs and the collaborative pairs in the reconstructed layouts' accuracy, because the experimental procedures should disrupt the retrieval process similarly for individuals and pairs. However, if the product of recall in a pair causes collaborative inhibition, then the difference between nominal and collaborative pairs in reconstruction accuracy should be significant, as it was in Experiment 1.

Experiment 2

Method

Participants Another 64 undergraduate students from Iowa State University participated in exchange for course credit. Sixteen of the participants were assigned to each of the two individual conditions, and 32 participants were assigned to the collaborative condition.

Stimuli and procedure After learning the layout, participants donned their blindfolds and the experimenter removed the objects from the rug and placed them in a box (instead of placing them at the back edge of the rug, as in Exp. 1). During reconstruction, the sequence of objects was randomly determined by the experimenter. The stimuli, design, and procedure were otherwise identical to those of Experiment 1.

Results

Reconstruction Figure 5 summarizes the reconstructed object locations for each object in each of the four conditions. For each object, 95 %-confidence ellipses (Batschelet, 1981) were constructed using the *X* and *Y* coordinates of each reconstructed object location. For nominal pairs, five out of ten confidence ellipses contained the actual object location, as compared to four for individuals from the 0º perspective, three for individuals from the 45º perspective, and one for collaborative pairs. The higher number of confidence ellipses containing the actual target location in the nominal group was not due to larger confidence ellipses. Confidence ellipses were numerically smallest for nominal pairs, followed by those for collaborative pairs and then individuals, although these data were not analyzed statistically.

Reconstruction accuracy was measured as the bidimensional correlation between the judged and actual object locations, which is shown in Fig. 6 as a function of learning condition. Pairs had significantly higher bidimensional correlations than did singles from the 0º perspective, $t(30) = 3.16$, $p = .004$, $d = 1.00$, but not significantly higher than singles from the 45º perspective, $t(30) = 1.63$, $p = .114$. Nominal pairs had significantly higher correlations than did collaborative pairs $t(30) = 3.14$, $p = .004$, $d = 0.71$.

To evaluate potential differences across the experiments, we conducted an ANOVA with terms for condition (individuals from 0º, individuals from 45º, and collaborative pairs) and experiment. Only the main effect of condition was significant, $F(2, 90) = 5.71$, $p = .005$, $\eta_p^2 = .11$. The main effect of experiment was not significant, nor was the interaction.

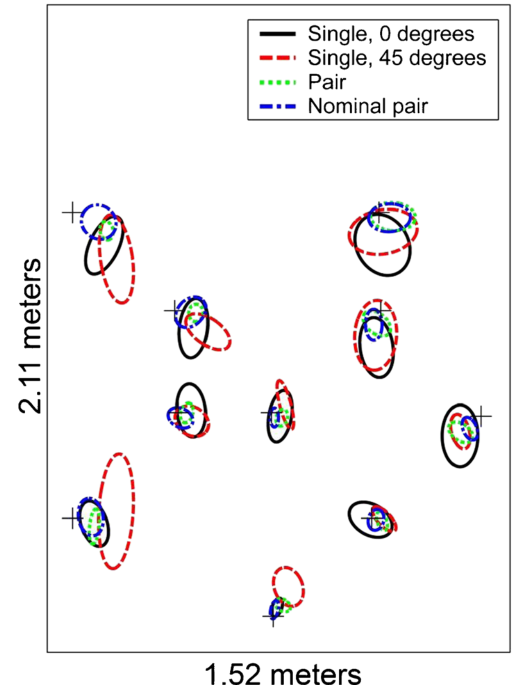

Fig. 5 Mean response locations and 95 %-confidence ellipses for the reconstructed layouts in Experiment 2. Plus symbols indicate the actual object locations, and ellipses are centered on the average response locations

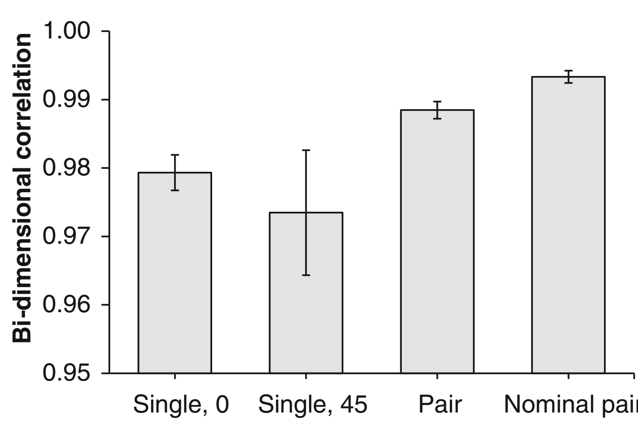

Fig. 6 Average bidimensional correlations on the layout reconstruction task in Experiment 2. Error bars indicate ±1 standard error

Judgments of relative direction Pointing errors were more responsive to the manipulation of the independent variables than were pointing latencies, and there was no indication of a speed–accuracy trade-off. Within-participants correlations between errors and latencies averaged .20 ($SD = .37$), which was significantly greater than zero, $t(63) = 4.40$, $p < .001$, $d = 1.12$. In the interest of brevity, we will focus on pointing errors.

As can be seen in Fig. 7, two major patterns are apparent from the pointing-error data. First, absolute pointing errors were lowest when participants imagined the perspective aligned with the studied view. In some cases, errors were also relatively low when imagining perspectives orthogonal or opposite to the studied view. This finding is consistent with the notion that participants established a reference frame aligned with the studied view, and that subsequent retrieval was facilitated when imagining the perspective(s) aligned with that reference frame. Second, the selected reference frame was not influenced by the presence of a partner.

These conclusions were supported by statistical analyses. Absolute pointing errors (Fig. 7) were analyzed in a mixed-model repeated measures ANOVA with terms for imagined perspective (0º–315º, in increments of 45º), study view (0º or 45º), and study condition (single or pair). The main effect of imagined perspective, $F(7, 420) = 8.64$, $p < .001$, $\eta_p^2 = .13$, was qualified by an interaction between imagined perspective and study view, $F(7, 420) = 4.04$, $p < .001$, $\eta_p^2 = .06$. No other main effects or interactions were significant. The interaction contrast comparing performance on the two studied perspectives (0º and 45º) across the two viewing conditions (0º and 45º) was also significant, $F(1, 60) = 21.04$, $p < .001$, $\eta_p^2 = .26$. Analyses of the participants who completed reconstruction individually indicated that JRD errors were significantly negatively correlated with bidimensional correlations on the reconstruction task, $r(32) = -.38$, $p = .032$, suggesting that both measures tap into the same underlying memory.

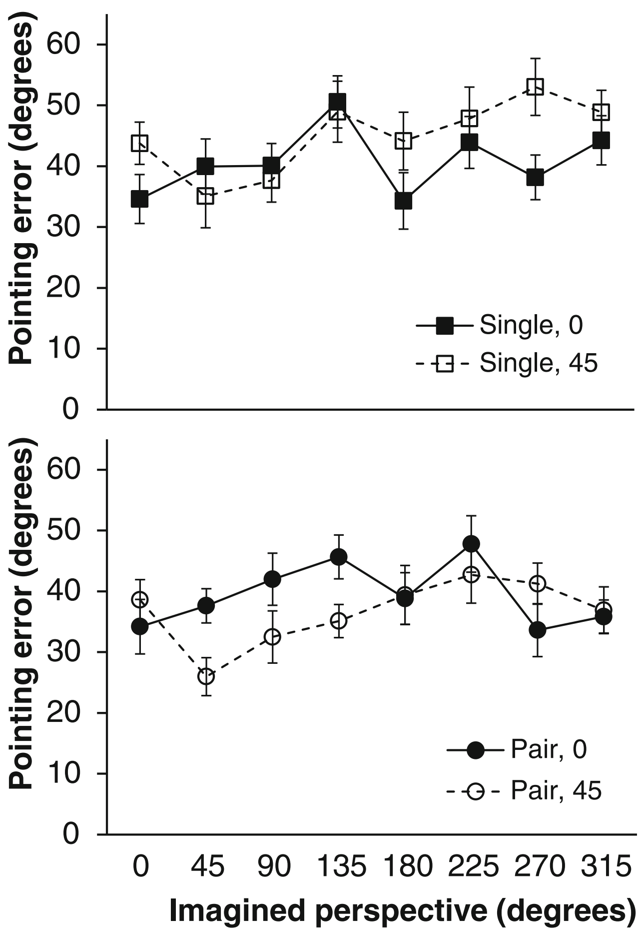

Fig. 7 Average pointing errors on the judgment-of-relative-direction task in Experiment 2, as a function of study condition (single or pair), study perspective (0º or 45º), and imagined perspective. Error bars indicate ±1 standard error

Discussion

The results of Experiment 2 mirror those found in Experiment 1, with the exception of the comparison between the bidimensional correlations for collaborative pairs and singles who learned from 45º, which failed to reach significance; this difference was in the expected direction, however. On the reconstruction task, collaborative pairs produced layouts that were equally as accurate or more accurate than those produced by individuals, but less accurate than those produced by nominal pairs. The latter finding is evidence for collaborative inhibition.

These results indicate that the source of collaborative inhibition in the present experiments may have been the product, not the process, of collaboration (Wright & Klumpp, 2004). Experiment 2 showed that disruption of the retrieval process for individual participants still resulted in collaborative inhibition, thereby providing evidence against process-based interference as the source of collaborative inhibition in the present paradigm. The lack of statistical differences across experiments, which varied in terms of the retrieval process, further supports this conclusion. It is possible, however, that our manipulation only affected isolated processes, and that other process-based effects could account for these results.

Additionally, performance on the JRD task indicated that participants selected a reference frame parallel to the perspective from which they had studied, and that reference frame selection was unaffected by studying as an individual versus a pair. This indicates that the spatial memories of participants who studied in pairs were organized similarly to those of participants who studied individually.

General discussion

In the present study, we sought to examine whether collaborative inhibition, which has been previously reported using traditional memory stimuli such as word lists and prose

(Andersson & Rönnberg, 1995; Ekeocha & Brennan, 2008; Finlay et al., 2000; Weldon & Bellinger, 1997), also occurs for another type of common collaborative retrieval task: spatial memory retrieval. In two experiments, spatial layouts reconstructed from memory by collaborative pairs were less accurate than those of nominal pairs, which were created by combining the responses of participants who had studied and retrieved individually. These results provide evidence that collaborative inhibition occurs during spatial memory retrieval, and indicate the generality of the phenomenon in a vastly different experimental paradigm.

The procedure used to study collaborative inhibition in Experiment 1, whereby participants were allowed to choose the object order during layout reconstruction, was insufficient to determine whether collaborative inhibition was caused by process-based or product-based disruption of retrieval (Wright & Klump, 2004). In the reconstruction task of Experiment 1, individual participants were allowed to choose their preferred object sequence, whereas collaborative pairs took turns choosing objects, thereby disrupting each pair member's preferred order, and potentially interfering with the retrieval process. Furthermore, collaborative pairs saw their partners' responses during reconstruction, potentially introducing product-based interference. In order to resolve these two potential causes of collaborative inhibition, all participants in Experiment 2 completed the reconstruction task using a random object order, determined by the experimenter. If the process of collaboration in Experiment 1 was the source of collaborative inhibition, then disrupting the retrieval sequences of all participants in Experiment 2 should have eliminated collaborative inhibition. Contrary to this hypothesis, collaborative inhibition still occurred in Experiment 2. This result distinguishes the present results from past work on collaborative inhibition, in which collaborative pairs performed no worse than nominal pairs during cued recall (Finlay et al., 2000) or when a specific recall strategy was enforced (Basden et al., 1997), both of which disrupted the retrieval processes of individuals and groups alike.

The fact that interfering with the retrieval process in Experiment 2 did not eliminate collaborative inhibition suggests that collaborative inhibition might be caused by the product of collaboration. The participants in both experiments were free to adjust the locations of every object, and such adjustments served to continually change the product of retrieval, perhaps increasing the product-based interference. However, it is possible that other, unexplored causes exist, and future studies will need to manipulate the presence of product-based interference in order to evaluate its role.

It is also possible that social factors play a role in collaborative inhibition. Social influences that have been proposed include familiarity among group members (Peker & Tekcan, 2009), whereby more-familiar group members could provide additional retrieval cues to their partner(s); social norms (Weldon & Bellinger, 1997), whereby group members may not want to interrupt the recall of their partner(s); and motivational factors (Weldon et al., 2000), such as social loafing in the presence of a collaborative partner. These and other social factors have been examined using traditional collaborative-inhibition tasks, but none have been found to account for collaborative inhibition.

Regardless of the mechanism underlying collaborative inhibition, the results of the present study may have implications for how group performance on a spatial task can be optimized. For instance, when a group attempts to locate a previously visited location by retrieving it from spatial memory, as commonly occurs when attempting to travel as a group from a conference location to a nearby restaurant, the group might perform better when each individual recalls the intended destination before the group discusses the planned route. The group would not be able to construct a collaborative layout following our exact laboratory methods because, presumably, they would not have access to the correct restaurant location to use as a reference when combining multiple layouts. However, another criterion for location selection could be used, such as the relative confidence of the group members in their memory for the restaurant location (i.e., "I know the restaurant was on Lake Street"). Future research may provide further insight into the application of our results to real-world collaborative navigation tasks.

The presence of a collaborative partner had no effect on the organization of individuals' spatial memories, as was determined by performance on the JRD task. Regardless of the presence of a collaborative partner, participants remembered the spatial layout using a reference frame selected from their initial study view. The lack of influence of a collaborative partner on reference frame selection is somewhat inconsistent with the results of past work. Shelton and McNamara (2004) found that participants who described a layout to a partner from a predefined perspective incorporated the described perspective into their mental representations of the layout. Furthermore, Galati et al. (2013) found that explicit instructions about the partner's perspective were not necessary, and that the mere co-presence of a partner was sufficient for the partner's perspective to influence spatial memory. However, participants in those studies were aware that they would be collaborating on a spatial task involving the studied layout, whereas participants in the collaborative-pair condition of the present experiments were not told that they would be interacting or collaborating with their partner until learning was complete. Therefore, these findings identify boundary conditions of the influence of one person's perspective on another person's selected reference frame, and indicate that mere co-presence is insufficient to influence reference frame selection, and that the expectation of future collaboration is probably required.

In summary, collaborative inhibition occurred in a spatial memory task that differed dramatically from past demonstrations of this phenomenon, which have typically used traditional memory stimuli such as word lists (e.g., Basden et al., 1997). Furthermore, collaborative inhibition was found not to be caused by interference with retrieval processes during collaboration, and might be caused by the product of collaborative retrieval.

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