A Collaboration Script for Nonverbal Communication Enhances Perceptual Fluency With Visual Representations

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Abstract: Visuals can help students learn only if they understand what visuals show. This involves perceptual fluency: the ability to automatically see meaning in visuals. To support perceptual fluency, instructional interventions support inductive learning by providing simple tasks that require quick attention to relevant features. Sociocultural research shows that collaboration affords nonverbal communication behaviors that helps students attend to visual features more quickly, which helps them acquire perceptual fluency. In contrast, cognitive research suggests that collaboration is ineffective for learning from simple tasks. Hence, we ask: Can collaboration via nonverbal communication enhance the acquisition of perceptual fluency? We investigated this question by examining how 10 dyads collaborate on simple perceptual tasks via nonverbal communication. We analyzed gestures and interviews about learning experiences. Further, we compared dyads' performance on perceptual activities to 28 students who worked on the activities individually. Our findings suggest that collaboration helps students acquire perceptual fluency with visuals.

Keywords: Perceptual learning, nonverbal communication, collaboration, implicit learning processes, visual representations

Introduction

Instruction in science, technology, engineering, and math (STEM) often uses visual representations (NRC, 2006) such as those in Figure 1. Visuals can help students learn content knowledge by making abstract concepts accessible (Ainsworth, 2006; Rau, 2017c). Yet, visuals can impede learning if students lack *representational competencies*—knowledge about how visuals show information relevant to scientific and professional practices (Ainsworth, 2006; NRC, 2006). Most instructional interventions focus on *sense-making competencies*, which allow students to explain how visuals show concepts. For example, chemistry students need to explain how two-dimensional Lewis structures depict a molecule's three-dimensional geometry. Students acquire these competencies via *explicit processes* involved in verbal explanation. Recent research suggests that students need a second type of representational competency: *perceptual fluency* (Kellman & Massey, 2013). Perceptual fluency allows students to quickly and effortlessly infer more than is explicitly shown in a visual. For example, chemists can mentally visualize a molecule's geometry based on its Lewis structure. Students acquire perceptual fluency via *implicit processes* involved in inductive and nonverbal learning from experience with many example visual representations (Kellman & Massey, 2013; Koedinger, Corbett, & Perfetti, 2012; Rau, 2017c). Activities that support perceptual fluency have been shown to enhance learning of content knowledge (Rau, 2017c).

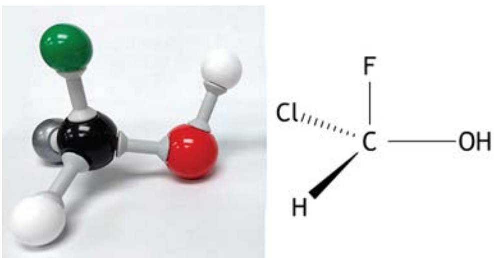

Figure 1. Ball-and-stick model (left) and wedge-dash Lewis structure (right) of a molecule.

Prior research has established that *collaborative activities* afford explicit processes that may enhance students' acquisition sense-making competencies (Dillenbourg, Baker, Blaye, & O'Malley, 1996; Rau, Bowman, & Moore, 2017). With respect to perceptual fluency, however, extant research provides conflicting views on whether collaboration may enhance or impede students' learning. In the following section, we review sociocultural research suggesting that collaboration may enhance perceptual fluency and cognitive research suggesting that it may impede perceptual fluency. This review leads to the question: Can collaboration enhance the acquisition of perceptual fluency?

We addressed this question in an exploratory study in which 10 dyads worked collaboratively on instructional activities that support perceptual fluency. These activities engage students in inductive nonverbal learning processes. To investigate whether students' collaborative interactions align with the learning goals of perceptual activities, we analyzed students' collaborative interactions. To investigate how students experience collaborating via nonverbal means of communication, we conducted semi-structured interviews. To investigate whether collaborative perceptual activities may be more effective than individual perceptual activities, we used log data generated by the activities to compare students' performance on perceptual activities to that of students who worked individually on perceptual activities in a prior study.

Prior research

Perceptual fluency with visual representations

Most research on learning with visuals has focused on explicit sense-making competencies (e.g., Rau, 2017c; Stieff, Hegarty, & Deslongchamps, 2011). Yet, recent research suggests that students also need implicit knowledge about visuals, referred to as perceptual fluency (Kellman & Massey, 2013; Rau, 2017c). This argument is based on observations that experts can quickly and effortlessly translate across visuals (Gibson, 2000). Experts "see at a glance" what visuals show without perceived mental effort (Kellman & Massey, 2013; NRC, 2006). They are so efficient at extracting information from visuals that it seems intuitive. For example, chemists automatically see that the visuals in Figure 1 show the same molecule. Perceptual fluency enables experts to effortlessly combine information from multiple visuals, to automatically translate among them (Kellman & Massey, 2013), and to use visuals to communicate with members of scientific and professional communities as if they shared a "visual language" (Kozma, Chin, Russell, & Marx, 2000). Perceptual fluency also allows experts to infer community-specific knowledge beyond what visuals explicitly show (Airey & Linder, 2009).

The sociocultural literature describes perceptual fluency as the product of implicit learning processes that allow students to induce a "visual language" by participating in disciplinary discourse (Wertsch & Kazak, 2011). For example, disciplinary discourse in chemistry often involves translating among multiple visuals (Kozma & Russell, 2005). When participating in such discourse practices, students rarely receive instruction on how to explain translations among visuals but rather infer such translations by imitating how other members of the community use visuals (Kozma & Russell, 2005), often without explicitly knowing what they show (Airey & Linder, 2009; Wertsch & Kazak, 2011). According to the cognitive psychology literature, students acquire perceptual fluency via perceptual-induction processes; that is, they induce connections among visuals without explicit instruction but through experience with many examples (Gibson, 2000; Kellman & Massey, 2013). Perceptual-induction processes are considered nonverbal and implicit because verbal reasoning is not necessary; they can even interfere with the acquisition of perceptual fluency (Schooler, Fiore, & Brandimonte, 1997).

Prior research yields a number of design principles for instructional activities that help students perceptually induce meaning from visuals. Such *perceptual activities* provide students with many examples in *simple* tasks that ask students to quickly judge what a visual shows (Kellman & Massey, 2013). Perceptual activities draw attention to relevant visual features by varying irrelevant visual features and contrasting them to relevant features. They encourage students to rely on perceptual intuitions about what they see rather than trying to explain what they see. Students get immediate feedback only on the accuracy of their response without conceptual explanations, so as to engage implicit rather than explicit processes.

Collaborative discourse and perceptual fluency

If students acquire perceptual fluency by participating in disciplinary discourse, it would seem natural to assume that collaborative activities would enhance students' acquisition of perceptual fluency. Indeed, students often use visuals in collaborative activities (Roschelle, 1992; Wertsch & Kazak, 2011). To date, most research on learning with visuals has focused on explicit sense-making competencies by investigating how students use visuals to collaboratively construct meaningful explanations of concepts (e.g., White & Pea, 2011). By contrast, research on perceptual activities has mostly focused on individual students (e.g., Kellman & Massey, 2013; Rau, 2017a). In the absence of empirical research on how collaborative discourse affects students' acquisition of perceptual fluency, it is perhaps not surprising that the literature on collaborative learning yields conflicting hypotheses as to whether collaboration may enhance or impede students' learning from perceptual activities.

On the one hand, sociocultural research on collaborative discourse suggests that collaboration affords implicit processes that enhance perceptual fluency. When collaborating, students use nonverbal means of communication like gesture to direct their partner's attention to relevant visual features (Singer, 2017). Indeed, analyses of collaborative discourse suggest that pointing at visual features helps students induce meaning of visuals (Rau, 2017b; Stevens & Hall, 1998). When participating in collaborative discourse, students imitate how their peers use visuals, which helps them become perceptually fluent in disciplinary practices of using visuals for problem solving and communication (Airey & Linder, 2009; Wertsch & Kazak, 2011). Thus, this literature suggests that collaboration could enhance students' acquisition of perceptual fluency via nonverbal communication.

On the other hand, cognitive research on socio-constructive processes suggests that collaboration may interfere with students' acquisition of perceptual fluency, for at least two reasons. First, the benefits of collaboration have largely been attributed to verbally mediated co-construction of knowledge (Dillenbourg et al., 1996). Yet, verbalization has been shown to interfere with the acquisition of perceptual fluency (Schooler et al., 1997). Second, perceptual activities involve simple tasks. Research suggests that collaboration enhances learning from complex but not from simple tasks because the latter are most efficiently done individually (Koedinger et al., 2012). Indeed, some studies shows that activities with simple tasks yield lower learning gains if they are done collaboratively than if they are done individually (Kirschner, Paas, & Kirschner, 2010). We note two limitations in these cognitive studies. First, these studies focused on learning explicit knowledge that was acquired via verbal processes. They did not test if collaboration enhances implicit learning of perceptual knowledge that is acquired via nonverbal processes. Second, they did not encourage nonverbal communication. Cognitive studies of individual learning show that nonverbal guidance of visual attention enhances learning with visuals (Jarodzka, van Gog, Dorr, Scheiter, & Gerjets, 2013), but the effects of nonverbal *collaboration* have not yet been tested.

Research questions

Given the conflicting views of prior sociocultural and cognitive research, our goal is to investigate whether collaboration can enhance perceptual fluency via nonverbal communication. To this end, we conducted an exploratory study that observed students collaborating on perceptual activities while being asked to use only nonverbal means of communication, such as gesture. Specifically, we investigate the following research questions:

1. How do students use gestures to direct each other's attention to features of visual representations?
2. How do students experience collaborating via nonverbal means of communication?
3. How does the acquisition of perceptual fluency compare between students working collaboratively versus individually on perceptual activities?

Method

Participants

Twenty bachelor and master students from a large university in the Midwestern U.S. participated in this study. They were recruited from undergraduate chemistry courses and flyers distributed across campus. Due to the exploratory nature of the study, their experience with chemistry ranged from no formal instruction to advanced undergraduate courses. Dyads were formed based on students' scheduling constraints.

Perceptual activities

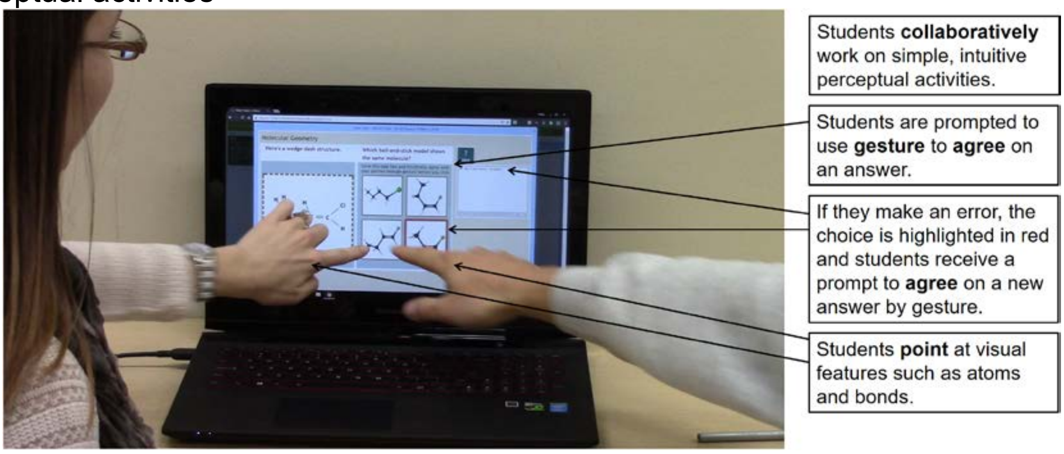

Figure 2. Example of students working in dyads on a collaborative perceptual activity.

Students worked on perceptual activities using an educational technology for undergraduate chemistry—Chem Tutor. These activities have been shown to enhance perceptual fluency (Rau, 2017a). The goal of these activities is to engage students in inductive processes. Figure 2 shows an example perceptual activity. Students are given one visual (Figure 2, left-hand side) and have to select one of four visuals that shows the same molecule (Figure

2, right-hand side). They are prompted to solve the task quickly and intuitively, without overthinking their answer. Answer choices are designed to direct attention to relevant visual features by contrasting relevant features. The contrasting cases were selected based on learner-centered studies that investigated which visual features expert chemists pay attention to, but novice chemistry students tend to confuse.

Students worked in dyads on 20 consecutive activities of the type shown in Figure 2. They solved these activities using a laptop computer with mouse and keyboard input. Chem Tutor contained a collaboration script that prompted students to point at the visual they think shows the same molecule, and to do so quickly and intuitively without overthinking the problem. The script prompted students to resolve disagreements only through nonverbal communication, such as pointing gestures. Once they agreed, they could submit the answer. If their answer was wrong, the script prompted students to agree on a new answer.

Procedure

Before students worked on the perceptual activities, they received a brief introduction explaining what perceptual learning is. Next, they were asked to try out this procedure on an unrelated perceptual activity that used different visuals. They were instructed to collaborate on these activities using only nonverbal communication such as gestures. They were told that they were not allowed to talk during the activity. Once comfortable with the method and after being given the opportunity to ask questions, students received 20 consecutive perceptual activities. The collaborative session was followed by a semi-structured interview during which students were asked to reflect on their experience with nonverbal communication during the collaborative session. The interviewer asked predefined questions about what was difficult, what was helpful, and whether gesturing helped them learn. The interviewer asked both participants, alternating which of the two students was to answer first. The interviewer also asked follow-up questions to clarify or expand on students' responses. All sessions were videotaped and interviews were transcribed.

Measures and analyses

To investigate how students used gestures to direct each other's attention to features of visual representations (research question 1), we segmented videos by perceptual activity. For each consecutive gesture (i.e., from the initiation of the hand movement to its finish), we coded which visual features students pointed at. To develop the coding scheme, we used a grounded approach to identify features that emerged across dyads. Interrater reliability, determined based on 10% of the data, was high (Kappa = .96). We compared these features to the learning goals of the perceptual activities, as determined by our prior research on novice students and expert chemists. The learning goals correspond to visual features that chemistry students often failed to attend to but experts considered important. Specifically, the goals of the perceptual activities are to direct students' visual attention to (1) distinct atoms in a molecule, (2) the total number of atoms in a molecule, and (3) the bonds between atoms.

To investigate how students experience collaborating via nonverbal communication (research question 2), we qualitatively examined interview responses for themes that emerged across dyads.

To investigate how collaborative acquisition of perceptual fluency compares to individual acquisition of perceptual fluency (research question 3), we computed error rates as the number of incorrect first attempts for each activity. Further, we computed answer-duration as the time between the previous and the current action (the start of the activity or an incorrect answer in the same activity until the current answer). Finally, we combined these metrics in an efficiency measure of how long it took students to achieve a correct answer, following Van Gog and Paas (2008) as: efficiency = (z-score of accuracy – z-score of duration) / $\sqrt{2}$. We used statistical analyses to compare error rates and answer-duration measures to those obtained from 28 undergraduate chemistry students who worked on the activities as an individual homework assignment for a chemistry course.

Results

Due to a technical issue, one of the ten dyads was missing video data for the first three of the 20 activities.

Nonverbal visual attention direction

We investigated how students use nonverbal attention direction to address research question 1. We used grounded analysis to identify codes to describe students' gestures. Three visual features emerged. Gestures were coded as *number of atoms* if students pointed at multiple atoms in a way that indicated counting, for example by indicating a number with their other hand. We coded gestures as *distinct atoms* if students pointed at particular atoms or groups of atoms that differed from other atoms in a molecule (e.g., a chlorine atom when all other atoms were carbons or hydrogens). Gestures were coded as *bonds* if students pointed at lines connecting atoms. In addition, we coded a gesture as *answer* if students pointed at an entire image rather than a particular feature. Further, we observed that on later activities, students seemed to point more often only at the entire answer image. Therefore, we also recorded whether an activity had only answer codes. Finally, we observed that students achieved an answer with fewer gestures over time. Therefore, we analyzed how the proportion of gesture types per activity changed over time by dividing the frequencies of codes by the number of total gestures used in the given activity. Table 1 provides an overview of the resulting metrics, categorized by quartiles of progress through the 20 perceptual activities.

Table 1: Visual features students pointed at during by quartile of their progress through the perceptual activities: average number of total gestures per activity; proportion of gestures that pointed at number of atoms, distinct atoms, bonds, or answer, and proportion of activities with answer gestures only

Quartile (Activities)	**Gestures per activity**	**Number of atoms**	**Distinct atoms**	**Bonds**	**Answer**	**Answer-only activities**
1 (1-5)	3.11	10.2%	13.6%	16.3%	56.1%	12.3%
2 (6-10)	2.32	8.6%	11.2%	15.5%	56.9%	13.8%
3 (11-15)	2.46	11.4%	8.9%	8.1%	52.9%	13.8%
4 (16-20)	2.18	15.6%	4.6%	12.8%	59.7%	20.2%

Given the small number of gestures per activity, a quantitative analysis of the gestures was not warranted. Instead, we qualitatively inspected patterns and trends over time. Overall, it is striking that students exclusively pointed at visual features that match the learning goals of the perceptual activities. Somewhat to our surprise, students did not point at other features such as bond angles or branching. Further, over time, we observed that students paid more attention to the number of atoms, whereas they paid less attention to distinct atoms and bonds. We also found that over time, dyads required fewer gestures to agree on an answer. Finally, students seemed to converge on more holistic processing over time, pointing more frequently at the entire answer choice and more frequently pointing only at the answer without additionally pointing at other features.

Student experiences with nonverbal communication

To address research question 2, we examined how students experienced nonverbal communication when collaborating on perceptual activities. The following themes emerged. First, with respect to *comfort*, several students commented that gesturing was uncomfortable at first but got easier with practice: "I feel like at the beginning, just 'cause we didn't really know exactly what the other person was saying, it was a little challenging, but towards the end we kind of like figured out, what we meant and then we ended up both doing the same gestures meaning for the same thing." Others reported being comfortable with gesturing: "I feel like that's easier than you telling me 'Oh, look at the green…' see I don't have words for the diagram, so, I think it was easier to just like point out why that was." Several students reported enjoying gesturing: "It felt like, a game almost."

Second, regarding *helpfulness*, all students reported that their partner's gestures helped them attend to relevant visual features: "you wouldn't have gotten it right on the, first try, you were pointing to something and you were like Oh yeah, I shouldn't have missed that." Students explained why they found gesturing helpful because it matched the perceptual nature of the task: "For this specific task, because it has to do with orientation, like how stuff is positioned, gestures often help versus just saying pointing up." Also, students found gestures helpful because they made them feel more confident about their perceptions than if they had worked on the activities individually: "I think I would have doubted myself more because I don't know a lot about chemistry." Further, students thought that gestures aligned with nonverbal communication in chemistry: "I think it reminded me that nonverbal communication is very key."

Third, students had conflicting experiences with respect to the *efficiency* of the collaboration process. Some students found collaboration inefficient. For example, when asked how the task would have been different if they had worked on the same activities alone, one students said: "I think I would have been faster but probably less accurate." By contrast, her partner expected to be more efficient when collaborating: "I think for me it's the opposite I think I would have taken my time and kind of gone through it more slower." Many students mentioned that they became more efficient at gesturing as a result of learning what features to attend to: "then he didn't have to point to it later on for me to be like the green is Cl."

Acquisition of perceptual fluency from collaborative versus individual activities

To address research question 3, we examined how students' acquisition of perceptual fluency differed between students working collaboratively versus individually. A t-test with error rates as dependent measure and collaborative versus individual work as independent factor showed a large effect such that students who worked collaboratively had significantly lower error rates, $t(36) = 8.27$, $p < .01$, $d = 1.05$. Further, we inspected students' learning curves, that is, how their error rates decreased as they progressed through the perceptual activities. Figure 3 shows that students' error rates decreased more quickly as a function of their progress through the perceptual activities when they worked collaboratively (purple) than when they worked individually (orange). Next, a t-test with answer-duration as dependent measure showed a large effect of collaborative work, such that students took significantly more time to submit an answer when working collaboratively, $t(36) = 5.92$, $p < .01$, $d = 3.18$. Finally, a t-test with efficiency as dependent measure showed no significant effect of collaborative work ($t < 1$).

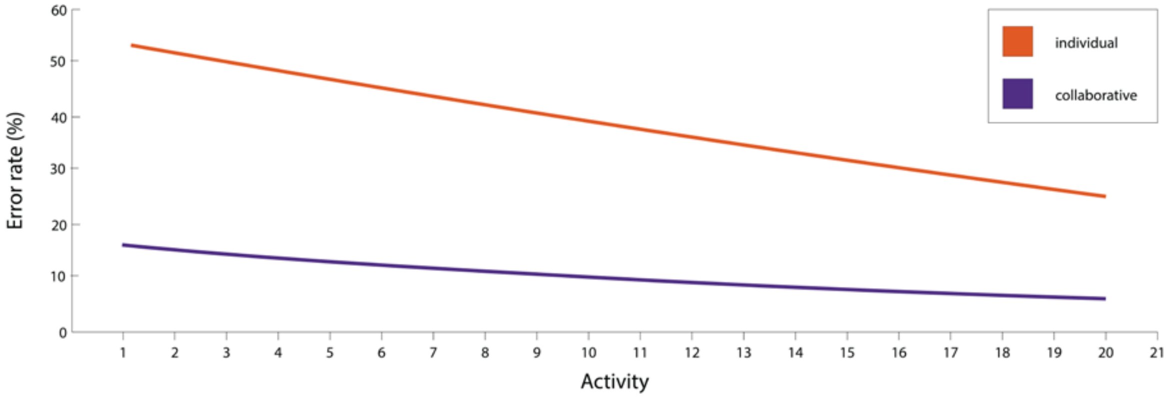

Figure 3. Learning curves of error rates decreasing over the course of 20 activities for students working collaboratively (purple) or individually (orange).

Discussion

On the one hand, sociocultural research on collaborative discourse suggests that nonverbal communication is a key process through which students acquire perceptual fluency in collaborative settings (e.g., Wertsch & Kazak, 2011). On the other hand, cognitive research on collaborative learning suggests that collaboration may interfere with students' learning. Specifically, this research has argued that (1) collaboration can reduce the effectiveness of perceptual learning because communication interferes with inductive processes (Schooler et al., 1997) and (2) collaboration can reduce the efficiency of perceptual learning because simple tasks are more efficiently done individually (e.g., Kirschner et al., 2010; Koedinger et al., 2012).

Our findings suggest that collaboration may indeed enhance students' acquisition of perceptual fluency from activities that support perceptual fluency with simple tasks. First, we found that students can use nonverbal communication to direct each other's attention to visual features that align with the learning goals of perceptual activities by pointing at the number of atoms in a molecule, distinct atoms, and bonds. Over time, students increasingly prioritize the number of atoms. Further, their gestures become more efficient: it takes students fewer gestures to achieve the right answer. Finally, students' gestures become more holistic over time: students point at the entire answer picture rather than at specific features. Because we had identified the learning goals of the perceptual activities based on features that expert chemists consider to be important, these findings suggest that students' gestures align with expert discourse practices.

Second, we found that after becoming familiar with the method, students felt comfortable with gesturing. Further, they experienced their partner's gestures as helpful for four reasons: (1) they helped them attend to visual features they otherwise would have missed, (2) they increased their confidence in their perceptions, (3) they align with the perceptual nature of the activities, and (4) they aligned with the use of nonverbal communication in chemistry discourse. With respect to efficiency, students' experiences were mixed: while some commented that they found nonverbal communication inefficient and would have preferred to talk, others thought it helped them become more efficient at the perceptual activities than they would have been when working alone.

Third, our comparison of the log data from this study to a prior individual study corroborates the analysis of the gestures and interviews. Specifically, we found that students indeed achieved higher accuracy in translating among the visuals when working collaboratively than when working individually. However, it took students longer to arrive at their answers when they worked collaboratively. When we combined accuracy and duration metrics into an efficiency measure, we found no evidence that the longer response times made students less efficient in collaboratively achieving a correct answer, compared to students working individually.

Our findings are surprising in light of prior cognitive psychology research. This prior research suggested that collaboration may reduce the effectiveness of perceptual activities because communication interferes with perceptual learning processes (Schooler et al., 1997). However, this prior research focused on verbal communication. Our findings suggest that nonverbal communication may actually enhance (rather than interfere) with perceptual learning. Further, prior research claims that collaboration may reduce the efficiency of learning from perceptual activities that provide students with many examples in simple tasks. Indeed, Koedinger and colleagues (2012) describe collaboration as an instructional intervention that enhances sense-making processes, which are time-consuming and therefore reduce the efficiency of students' learning from simple tasks that do not require sense making. Our findings agree that collaboration takes time, but—counter to the argument by Koedinger and colleagues—we found no evidence that the increase in duration came at the expense of overall efficiency. Rather, increase in duration is associated with higher accuracy. These quantitative findings corroborate the qualitative analyses of gestures and interviews that suggest that the extra time required to collaborate is worthwhile because it is associated with higher confidence and because students learn to engage in nonverbal communication practices that align with what expert chemists pay attention to when working with visuals.

To summarize, our study makes two important theoretical contributions to prior research on collaborative learning. First, we provide empirical evidence for the argument in the sociocultural literature that nonverbal communication is a key process through which students collaboratively induce meaning of visuals. We readily concede that one can hardly consider our study setup a representative example of disciplinary discourse—being a rather artificial learning situation in a research lab. Yet, we believe that our ability to show that nonverbal communication can enhance perceptual fluency even in an artificial setting all the more underscores the importance of collaboration for perceptual learning. Second, we expand prior cognitive research on collaborative learning by showing that simple tasks focused on implicit, nonverbal knowledge can be learned more effectively in collaboration with partners, provided that the activities focus on implicit, nonverbal knowledge and encourage nonverbal rather than verbal communication. This finding suggests that there may be a new boundary condition for the effectiveness of collaborative learning from simple tasks.

Our study makes two practical contributions. First, it suggests that to support students' acquisition of perceptual fluency, instruction should not disregard collaborative activities. We find that collaborative perceptual activities can enhance students' acquisition of perceptual fluency. In light of prior cognitive research, however, we recommend encouraging students to communicate via nonverbal means like gesture. Second, our findings suggest that collaboration scripts that prompt students to use gestures to collaborate and prohibit verbal communication may be effective at enhancing collaborative learning from simple tasks—as opposed to complex tasks that benefit from collaboration scripts that support verbal communication.

Limitations and future directions

Our contributions should be interpreted against the following limitations. First, our study was conducted in a research lab. This is not representative of most realistic collaborative learning activities. Especially in light of the argument that perceptual learning occurs while students engage in disciplinary discourse practices, future research should investigate whether prompting students to use nonverbal communication enhances their acquisition of perceptual fluency in realistic learning contexts. Second, we did not assess students' prior knowledge or their prior perceptual fluency. Future research should include additional assessments to investigate whether collaboration may differentially benefit students with low or high prior knowledge. Third, we did not investigate whether collaborative perceptual learning helps students participate in verbal disciplinary discourse. Future studies could investigate this question by observing how students communicate verbally after having worked on perceptual activities either individually or collaboratively. Fourth, we did not test whether collaborative perceptual activities are more effective than individual perceptual activities at enhancing learning of content knowledge. Given that perceptual fluency enhances learning of domain knowledge (e.g., Kellman & Massey, 2013), we expect that the enhanced acquisition of perceptual fluency that we observed when students were learning collaboratively increases their acquisition of content knowledge. Future research should investigate this hypothesis by assessing students' individual content knowledge. It would be interesting to test effects on content knowledge immediately after collaborative perceptual activities and after subsequent instruction that uses the same visual representations (e.g., ball-and-stick models and Lewis structures) for different chemistry concepts.

Conclusions

Our exploratory study provides valuable directions for future research. It demonstrates that collaboration via nonverbal communication can enhance perceptual learning in a controlled setting. We believe this finding also demonstrates the importance of nonverbal perceptual processes for collaborative learning. In our opinion, cognitive psychology research was too quick to dismiss the potential benefits of collaborative activities for learning from simple tasks because it did not consider nonverbal perceptual learning. By addressing this gap in the literature, our study bridges sociocultural and cognitive research on collaborative perceptual learning. In general, our results illustrate that cognitive psychology research on collaborative learning can benefit from aligning instructional supports with disciplinary practices documented in the sociocultural literature.

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