Using Real-Time Gaze Feedback and Interventions to Facilitate Coordinative Behavior: An Investigation With Recurrent Analysis

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Abstract: Real-time gaze feedback is useful in improving collaborative processes in learning environments with low awareness of others, such as distant collaborative learning settings. Recent studies have integrated artificial intelligence, such as pedagogical conversational agent (PCA), into such settings; however, the types of PCA interventions that will produce synergy remain unclear. A laboratory experiment was conducted to investigate how PCA's metacognitive interventions on gaze awareness facilitate coordinative behaviors and learning processes during an explanation task. Using two eye trackers, this study analyzed the degree of gaze recurrence and coded the degree of the collaborative process. The coding results showed that the interventions improved the collaborative process of coordination but did not facilitate recurrence. However, the results showed correlations between the collaborative process and gaze recurrence, with a greater number when using PCA with real-time gaze feedback. Therefore, integration of gaze feedback and interventions may lead to collaborative learning systems improvements.

Introduction

Studies in collaborative learning have shown how peer explanation activities provide opportunities for metacognition and self-regulation (Roschelle, 1992) and how constructive and interactive conversations between learners deepen their understanding through externalizing thoughts. Chi's (2009) ICAP theory demonstrated that the transitions of the learner's state, such as from passive to active and from constructive to interactive, are the key to deepening the understanding. Studies in classrooms have been conducted based on these theoretical implications in the fields of learning and cognitive science, such as in active learning (e.g., jigsaw learning). Several studies have been conducted to further design collaborative support systems by investigating the types of interventions (Rummel et al., 2009) and facilitations that help learners improve interactions and performances during peer learning. Integration with artificial intelligence in collaborative learning and the use of pedagogical conversational agents (PCA) have been studied in various environments (Graesser et al., 2005). These studies have shown that the use of PCA can facilitate learners' metacognitive activities, leading to richer interactions compared with not using such systems (Hayashi, 2019).

Considering that peer explanation activities require collaboration skills, such as coordinating with others and establishing common ground (Clark & Brennan, 1991), investigating the types of technologies that can be used for such activities in an online environment is a challenge. It has been widely studied and experienced using communication tools, such as online conferencing applications that do not provide the same reality as in-person interactions. The lack of communication channels and awareness has been an important topic in computer-supported collaborative work, and research has been conducted to develop new interfaces and devices that can close the gap between in-person and online interactions. "Video Tunnels" are an early system that can provide awareness of the co-located partner by conveying their gaze gestures (Ishii et al., 1993). Furthermore, eye trackers have become widely used to provide gaze awareness by directly recording and presenting the partner's gaze information. However, the knowledge on the conditions under which the use of these technologies would be advantageous in explanation activities performed in online and distance collaborative learning is insufficient.

Past study by Hayashi (2020) investigated how the combination of real-time gaze feedback and metacognitive facilitation from a PCA facilitates peer learners' explanation performance and process. Using a jigsaw-like explanation task, the previous study investigated these two technologies in a factorial experimental design. The results showed that PCA interventions facilitated better learning gains than gaze feedback alone. However, the results did not show clear evidence of the synergetic use of both technologies, and correlations between the collaboration process and performance were found in the conditions where learners used both technologies. Quantitative analysis showed that if learners were able to notice that they could actively use their gaze during their interaction, they could perform efficiently in the explanation activity. This result further suggests that if PCA can provide metacognitive facilitation, including the use of gaze gestures with the system, learners may be able to effectively utilize both gaze feedback and metacognitive suggestions. This study will thus investigate this point by adding new interventions from the PCA regarding the real-time gaze feedback to facilitate learners to better coordinate with each other. To investigate this point, this study used recurrence metrics to capture the degree of the effect.

Previous studies in cognitive science, such as Richardson and Dale (2005), have found that the degree of gaze recurrence between dyads (i.e., speaker–listener) is correlated with understanding and establishing common ground. They investigated how dyads engaged in conversations by looking at a shared picture presented on a computer monitor and found that, during these conversations, both the speaker and listener physically gazed at the same area on the monitor. Moreover, using a technique called "cross recurrence analysis," they found that the gaze patterns of the dyad members synchronized over time. They also showed that the degree of synchronization correlates with comprehension tests such as memory retrieval and understanding. Following these findings, studies on computer-supported collaborative learning involving gaze recurrence and techniques such as real-time mutual gaze perception have shown that gaze synchronization helps produce a better collaborative learning process (Schneider & Pea, 2013). Gaze synchronization is important for successful communication; this index can be applied to the understanding that the more the learners looked at the same area on their screen, the more attention they paid to each other (joint attention). Considering these findings, the present study uses the recurrent index to understand the degree of successful coordination and investigates how real-time gaze feedback and PCA intervention influence the recurrent index.

Therefore, this study investigates how the combination of gaze feedback and PCA metacognitive interventions, including gaze, facilitates the learning process by comparing conditions in which learners make explanations with and without PCA under real-time gaze feedback. Analysis was conducted by both post-evaluation of conversation and gaze recurrence indices collected from eye movements of the dyads. The hypotheses are as follows:

- H1: Collaborative learning processes are facilitated when learners use metacognitive interventions, including gaze awareness, compared with no interventions.
- H2: Gaze recurrence is facilitated when learners use metacognitive interventions, including gaze awareness, compared with no interventions.
- H3: The correlation between the learning process and recurrence will be stronger when learners use metacognitive interventions, including gaze awareness, compared with no interventions.

Method

Participants

Eighty Japanese university students participated in the experiment in dyads. The participants (referred to as learners) received course credit for their participation. This study was approved by the ethical review committee at the author's institution.

Experimental task and procedure

Task

The task was to explain a topic in cognitive science (e.g., human information processing in language perception) using two technical concepts (i.e., top-down and bottom-up processing). This study adopted the jigsaw method [1], which is a style of learning in which each learner has knowledge of one sub-concept and exchanges it with their partner through explanation. The learners' goal was to explain their knowledge based on the distributed sub-concepts and provide an overall integrated explanation of the phenomenon using the two sub-concepts. The learners started the task by explaining each different type of concept assigned to them before the explanation task began. Upon starting the task, they were asked to first read the sample description of their topic and then explain its meaning in relation to the topic. Learners were free to ask questions and discuss the concept with their partners; after one learner had finished explaining one sub-concept, they switched roles, and the other learner explained the other sub-concept.

System

The experiment was conducted using a redeveloped version of the system designed in a previous study (Hayashi, 2020). The learners sat in front of a computer display and spoke to each other. The experimental system was developed in Java and run on an in-house server–client network platform. The two learners' computers were connected through a local area network, and task execution was controlled by a program on the server side. The study used two eye trackers (Tobii X2-30) for gaze feedback; a program was developed to show the gaze of the partner during the task as a red square in real time. Since the participants were instructed to begin by reading the text on their screens, it was expected that while one partner explained their concept while looking at the area with the explanation of their concept, the listener would also look at the same area during that time. The system featured a PCA that provided metacognitive suggestions to facilitate the explanations (Hayashi, 2020). In a previous study, five types of metacognitive suggestions were used, such as reminding learners to achieve the task goal and facilitating metacognition (Azevedo & Cromley, 2004). In this study, we additionally implemented metacognitive prompts that mentioned real-time gaze feedback. These included comments on (1) how their partner's gaze will help their awareness of their partner's attention on the learning material and (2) how gaze coupling will lead to a better quality of the collaborative activity. To provide these suggestions, an embodied PCA, which physically moved when it spoke, was presented at the center of the screen. Below the PCA was a text box containing messages. The experimenter sat on the side of the experimental room and manually instructed the PCA to provide metacognitive suggestions. Suggestions were made once per minute, when there was a gap in the conversation. A microphone was placed next to each learner, and all audio data were transcribed manually.

Measures

Collaboration process

This study adopted part of the coding scheme from Rummel et al. (2009). The original full scheme was as follows: 1 = mutual understanding, 2 = dialogue management, 3 = information pooling, 4 = reaching consensus, 5 = task division, 6 = time management, 7 = reciprocal interaction, and 8 = individual task orientation. Two coders evaluated the transcripts of the experiment dialogues, with a coding match of 89.7%, and used the median score for analysis of the discrepancy evaluations.

Gaze recurrence

Using gaze data, this study investigated the degree to which each learner looked at the same area on a screen. The area was categorized according to areas of interest as follows: (1) area 1 = left frame box (self/other concept), (2) area 2 = right frame box (self/other concept), (3) area 3 = middle frame box (PCA), and (4) other. The fixation coordinates from the eye-tracking gaze log files of each participant were labeled. Next, based on Richardson and Dale (2005), the labeled data were analyzed using a recurrence analysis to capture the proportion of fixations at the same location for both learners in a typical time state. The analysis was conducted using R software. The recurrence of *phi* observed between the two time series of the two learners was calculated for a specific time *k*. The *phi(k)* coefficient increases with the frequency of matching recurrence simultaneously (*k*; *k*) and decreases with the frequency of mismatching. Based on the procedure used by Richardson and Dale (2005), the author adopted a time lag of 3 s. For each pair, the recurrence during each time lag was calculated, and the maximum value was used as the representative index for each learner and for further statistical analysis.

Results

To investigate the effects of each factor on the collaborative process, a 2 × 8 mixed-factor analysis of variance (ANOVA) was conducted for each coding scheme of the collaborative process. The results show that there was a significant interaction ($F(7, 546) = 4.615$, $p = 0.0021$, $\eta_p^2 = 0.0410$). Simple main effects show that learners with interventions outperformed those without interventions for each coding scheme: mutual understanding ($F(1, 624) = 19.265$, $p = 0.000$), dialogue management ($F(1, 624) = 9.097$, $p = 0.0027$), information pooling ($F(1, 624) = 27.794$, p = 0.0000), reaching consensus ($F(1, 624) = 18.837$, $p = 0.0000$), task division ($F(1, 624) = 11.785$, $p = 0.0006$), time management ($F(1, 624) = 17.377$, $p = 0.0000$), reciprocal interaction ($F(1, 624) = 12.993$, $p = 0.0003$), individual task orientation($F(1, 624) = 5.989$, $p = 0.0147$).

Table 1
*Results of the Correlations Between the Collaborative Process and Gaze Recurrence. *p<0.05.*

coding scheme	no intervention	intervention
1. mutual understanding	0.246	0.309*
2. dialogue management	0.240	0.400*
3. information pooling	0.061	0.295*
4. reaching consensus	0.262	0.121
5. task division	0.215	0.017
6. time management	0.232	0.256
7. reciprocal interaction	0.318*	0.029
8. individual task orientation	0.026	0.395*

To investigate how gaze recurrence differed according to each condition, one-way ANOVA was conducted. However, the results show that there was no significant difference between the two conditions ($F(1, 78) = 0.290$, $p = 0.5918$, $\eta_p^2 = 0.0037$).

Table 1 shows the results of the correlations between collaborative process and gaze recurrence. The results of Pearson's coefficient show that there were significant relationships in one coding scheme for the no-intervention condition and in four coding schemes for the intervention condition (Table 1). This indicates that the collaborative process is correlated with gaze recurrences, and this tendency appears more rapidly when the PCA intervention is provided.

Discussion and conclusions

This study investigated whether the use of metacognitive interventions from PCA, including real-time gaze feedback, facilitates collaborative processes during explanation activities. The results of the learning process show that all evaluation indexes were higher in the condition using the interventions from the PCA than in the condition without the interventions. This result supports H1 and provides new evidence of using PCA with real-time gaze feedback, which was not found in Hayashi (2020). A new challenge of this study was to investigate the differences using gaze recurrence; however, the results of the gaze recurrence did not show that PCA intervention influenced the coupling of the gaze. Therefore, H2 was not supported. However, the correlation between collaborative processes and gaze recurrence shows interesting results. There was a greater number of positive correlations between the two in the intervention condition (4/8) than in the no-intervention condition (1/8). This result supports H3 and indicates that learners who successfully coordinated their gaze also interacted to improve cooperative conversational behavior. This suggests that integrative designs of gaze feedback and interventions may lead to improvements in gaze awareness technologies implemented in collaborative learning systems. Further investigation should examine the relationships between learning performance and the type of interactions during explanation activities. Technologically, improvements in adaptive facilitation, such as providing feedback when gaze recurrence is being detected, are future challenges.

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