Eye-Write: Gaze Sharing for Collaborative Writing

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ABSTRACT

Online collaborative writing is an increasingly common practice. Despite its positive effect on productivity and quality of work, it poses challenges to co-authors in remote settings because of limitations in conversational grounding and activity awareness. This paper presents Eye-Write, a novel system which allows two co-authors to see at will the location of their partner's gaze within a text editor. To investigate the effect of shared gaze on collaboration, we conducted a study on synchronous remote collaborative writing in academic settings with 20 dyads. Gaze sharing improved five aspects of perceived collaboration quality: mutual understanding, level of joint attention, flow of communication, level of negotiation, and awareness of the co-author's activity. Furthermore, dyads whose participants deactivated the gaze visualization showed a smaller degree of collaboration. Our findings offer insights for future text editors by outlining the benefits of at-will gaze sharing in collaborative writing.

CCS CONCEPTS

• **Human-centered computing** → Collaborative content creation; Synchronous editors;

KEYWORDS

Eye tracking; shared gaze; collaborative writing

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1 INTRODUCTION

Collaborative writing is an increasingly integral part of professional and academic work. Experts in business, engineering, and law report that they write together more often and more complex than ever before [18, 48]. As such, a rich set of web-based collaborative writing systems has been developed, including tools such as Google Docs and Overleaf that enable new ways of writing together. In particular, synchronous writing, which refers to two or more people editing a document simultaneously, has emerged as a widely adopted practice. In contrast to the early 2000s, when synchronous editing was not well-received [24], a recent study focusing on undergraduate students showed that 95% of student teams used synchronous writing in their collaboratively-written class assignments [41]. The popularity of collaborative synchronous writing creates challenges and opportunities for researchers as well as the developers of such editors.

In this paper, we focus on the collaborative synchronous writing experience in remote settings. It is crucial to consider the increasing level of distributed work as the number of employees working primarily from a location outside of their place of employment has tripled over the past 30 years [31]. The significance of remote collaboration was reflected in a survey we conducted on collaborative academic writing, where 73% of the respondents had participated in remote collaborative writing at least a few times in the past year.

Our work draws inspiration from research that has shown the benefits of writing together at a distance. For example, a study showed that distributed groups who used an internet-based collaborative writing tool that enabled synchronous editing produced lengthier documents of higher quality than groups that used traditional word processors [30].

However, it is challenging to maintain group awareness and mutual understanding while writing together in a remote setting. In addition to the overall complexity of the collaborative writing process, the physical distance between co-authors creates further challenges. Contrary to co-located, remote computer-supported cooperative work tools often limit implicit references such as deixis or gaze direction [37]. Therefore, specialized collaborative writing platforms need to provide enhanced coordination, group awareness, and collaborative writing activity support [30]. One possibility to improve these aspects is to build awareness tools that improve the comprehensibility of discussion about the document as well as allow efficient use of references [4]. In previous research, this has been achieved with the use of dual eye tracking technology, however, the context has been limited to collaborative game-playing [23, 35, 36] and pair programming [10, 37]. No prior studies have combined research in synchronous collaborative writing and gaze visualization.

The goal of this research is to study the potential usefulness of gaze sharing during the process of collaborative writing. In addition, we examine the effect of gaze sharing on the level and quality of collaboration by conducting a study on dyads (i.e. pairs). The study focuses on academic writing as its constraints on time-efficient delivery and length of text are likely to promote synchronous collaborative writing.

We developed Eye-Write, a novel tool that incorporates gaze awareness functionality, to investigate the effect of gaze sharing on collaboration. Eye-Write extends the open-source collaborative text editor Firepad. Based on dual eye tracking technology, it visualizes the gaze location of each co-author and overlays it in real time on each of the active viewports of the mutually-edited text document.

Research hypotheses

Building upon the existing research on collaborative writing and shared gaze awareness, we conduct a study using Eye-Write that is guided by the following hypotheses:

H1: Remote dyads have a higher level of collaboration when they share their gaze location during synchronous collaborative writing process.

H2: The perceived quality of the synchronous collaborative writing process increases when a remote dyad shares their gaze location.

H3: Remote dyads finish collaborative writing tasks faster when they share their gaze location.

2 RELATED WORK

Collaborative writing is an iterative and social process that involves a team focused on a common objective that negotiates, coordinates, and communicates during the creation of a common document [29]. Writing together has been shown to promote learning and encourage initiative, creativity, and critical thinking [26]. Recently, many scholars have become interested in synchronous remote collaborative writing, for example, in academic settings [46]. Collaboration at distance has also become a center of interest for researchers in the field of eye tracking. With the use of dual eye tracking technology, the shared gaze awareness has shown potential as a means to facilitate communication in remote problem solving [8, 10]. In this section, we explore literature on collaborative writing and eye tracking.

Collaborative Writing

Research in collaborative writing dates back to the late 1980s when academics became interested in building systems to support the process of cooperative writing [15]. In the following decades, the rise of co-authorship in science, technology, medicine, and social sciences [6, 20] inspired researchers to deeper investigate collaborative writing. Studies have demonstrated that compared to individual work, collaborative writing has significant advantages [42]. For example, Putnis and Petelin showed that writing together promotes higher quality documents, higher levels of motivation, valuable feedback in draft stages, opportunities for less experienced writers to improve their skills, enhanced work relationships, and higher levels of acceptance of the final document [44].

To support the growing need for collaborative writing, researchers developed systems with features that accommodate different group dynamics. Among the first tools that enabled multiple users to co-edit the same document from different computers were Quilt [15], ShrEdit [40], SASSE [2], and MESSIE [45]. Recently, the focus of research shifted to cloud-based online writing. The increasing popularity of Web 2.0 applications, such as Google Docs and Overleaf, has sparked research interest in new forms of collaboration that allow groups to write together such as wiki-based collaborative writing [25] and synchronous writing [5, 9, 50].

Recent research has shown that online collaborative writing (OCW) tools have high potential in academic writing [7, 9, 25, 27, 41]. Through an extensive examination of undergraduate collaborative writing assignments, Olson et al. found that 95% of Google Docs-based coursework exhibited synchronous writing [41]. The same study revealed a correlation between the length of simultaneous writing sessions and an earlier turn-in. In addition, a comparative study between groups working face-to-face and students writing an assignment together in Google Docs showed that participants using the online text editor gained higher mean scores while also showing high levels of collaboration [47].

Although OCW systems allow remote collaboration, writing together at a distance requires specific features to support task awareness, communication, and coordination [4, 22].

Figure 1: The experiment setup. Participants faced opposite directions and worked on separate computers. Communication was achieved through Skype. A Tobii 4C eye tracker was placed at the bottom of each screen.

Birnholtz et al. discovered that communication is particularly important from a relational standpoint when participants are writing together in a remote synchronous mode [5]. Recent works have also shown the importance of visual support systems in OCW processes. For example, tools such as learning analytics visualization and group awareness functionality increase student engagement in OCW [27, 28]. Among the many ways of sharing information between writers, we are interested in real-time gaze sharing since it has been proven to facilitate communication in tightly-coupled collaborative tasks by providing an alternative non-linguistic channel for checking one's own and the co-author's understanding of what was said [33]. Our paper explores the use of gaze as a means to facilitate communication for writing partners by allowing the use of non-verbal cues. We also consider gaze as a potential means to enable remote collaborators to passively monitor each other's activity, as it has been shown to aid collaboration in collocated settings [22]. However, no OCW tool until today has enabled researchers to study the potential benefit of the natural visual cues of the co-authors' gaze to the OCW process. Our work builds on the aforementioned findings by developing and evaluating a novel system that provides co-authors with real-time gaze visualizations as an awareness tool which has been proven to improve communication and joint attention.

Eye Tracking and Collaboration

Researchers have long suggested the potential of dual eye tracking technology to better understand collaboration [23, 39]. The advances in eye tracking technology as well as the release of less obtrusive eye trackers have fostered research in remote collaboration where shared visual attention is particularly important, for example in supporting situation awareness and conversational grounding [17]. In recent years, scholars in eye tracking have examined mutually-shared gaze in remote collaborative tasks. Real-time mutual gaze perception has been investigated as a means to understand the process of collaborative reference [16], establish joint visual attention [46], and improve physical task performance [1, 19, 21]. For example, Schneider and Pea found that real-time mutual gaze perception intervention helped students achieve a higher quality of collaboration and a higher learning gain [46]. This finding is further supported by a study that showed the benefits of gaze sharing in terms of improving communication in pair programming [10].

Most previous studies on the use of gaze visualization in remote collaboration have focused on visual tasks [3, 11, 12, 14] where the potential benefits of gaze sharing are intuitive. In our study, we investigate shared gaze specifically in the context of synchronous collaborative writing, where the perceptual component is more subtle, albeit significant. We conducted an experiment in a novel setup with two eye trackers where participants had independent and not mirrored viewports. In addition, we examine the potential of at-will gaze sharing where users can enable and disable the gaze visualization, allowing for more intentional use of the tool.

3 PRELIMINARY SURVEY

To inform our study, we conducted a survey on academic collaborative writing practices. The survey was distributed to undergraduate and graduate students, professors, and researchers via mailing lists and social media. The data were collected using the survey tool Qualtrics. Participants could enter their emails in a lottery for a 50 USD gift card.

The survey investigated the respondents' familiarity and the ways in which they had used OCW tools in the past. We used multiple-choice questions inquiring about the participants' occupation, prior experience with collaborative academic writing in offline, online, asynchronous, and synchronous modes as well as the number of collaborators, and mode of communication between them. Further, two open-ended questions required respondents to list the three most positive and negative aspects of asynchronous and synchronous academic writing. The responses were coded using the analytic category identification of grounded theory [49]. The reported percentages reflect the proportion of respondents who identified the given aspect as positive or negative.

We received 126 responses. Most participants were between the ages 18 and 29 (79%) and included undergraduate (33%) and graduate students (51%), and professors (7%).

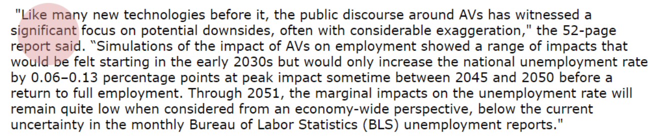
The responses supported prior research that shows the popularity of online collaborative writing. The majority of respondents (78%) had used OCW tools in synchronous mode for academic writing. A small number indicated that they had never used OCW tools (11%), or had not used them in synchronous mode (11%). Participants who used OCW tools in synchronous mode had done this so that they could edit (38%), follow the edits made by others (31%), or discuss the writing in real time with co-authors (28%). Most of the respondents that had used these tools said that they did so a few times in the last year (60%), with smaller groups stating they had used these tools every month or every week.

Among the 73% of the respondents who had used the OCW tools in a remote setting, those writing only in asynchronous mode reported that they communicated with their writing partners via e-mail. Those who used them in synchronous mode worked in groups of two or three collaborators (45% and 42% respectively), with instant messaging being the most common form of communication. The popularity of instant messaging may be attributed to the incorporation of chat-rooms in synchronous writing tools. Further, 28% of respondents that used asynchronous and 20% that used synchronous writing tools used some sort of audio-based communication, such as Skype or a phone call, to communicate during collaboration. Those who had not used OCW tools in remote settings said that spatial proximity to their collaborators made it easy to work in the same physical space. Some respondents noted that current tools do not provide adequate support for remote communication.

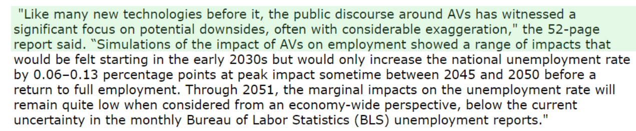
Respondents with experience with synchronous tools reported as positive aspects the efficiency of collaboration (51%) and the fast and effective communication between collaborators (22%) and as negative the unhelpful interactions with collaborators (37%) and technical limitations (22%).

4 EYE-WRITE

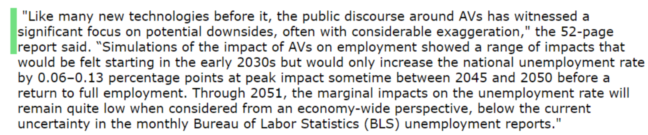
Informed by the survey responses, we developed Eye-Write, a novel gaze sharing system for collaborative document editing. We implemented Eye-Write as an extension to Firepad, an open-source collaborative text editor. By default, Firepad indicates the location of a co-author's cursor along with any text they have highlighted. With Eye-Write, the cursor is complemented by the gaze locations of each author, which are continuously captured from their eye tracker and



(a) Circle



(b) Block



(c) Bar

Figure 2: The visualizations that were tested to indicate where the co-author's gaze is located before concluding to the gradient visualization shown in Figure 3.

streamed to their co-author using a Firebase database. In our setting, we explore the support of only two authors.

We tested four visualization designs to indicate the location of the co-author's gaze on the screen. First, we experimented with a circle of a radius of the height of two lines of text so that it would correspond to the average fluctuation of the gaze predictions, effectively steadying their jitter. Second, we highlighted, as a block, the range of the three lines that the co-author was likely to be looking at. Third, following [10], we provided a vertical bar on the left margin of the text with a height corresponding to three lines of text. Finally, we experimented with a gradient visualization that indicates a range of three lines that the co-author's gaze falls, as well as its x-coordinate. The three lines of text are enclosed in two horizontal lines with the x-coordinate indicator represented as a rectangle centered on the predicted x-coordinate with a smoothed linear gradient. The visualization is only shifted up or down if the user's gaze falls outside the range of three lines. In all four cases, a user can see their co-author's gaze but not their own. If their gaze locations overlap, the visualization turns green, as in [10]. Figure 2 shows the first three of the aforementioned visualizations.

We conducted an iterative experiment to receive feedback on the most effective visualization. The process included 3 pairs collaboratively working on a writing task in a setup identical to the experiment. Each pair was given 10 minutes with each of the four visualizations. Users freely interacted with the gaze visualization tool without the time pressure to complete the writing task. After each 10' block, pairs described and evaluated the gaze visualization design in terms

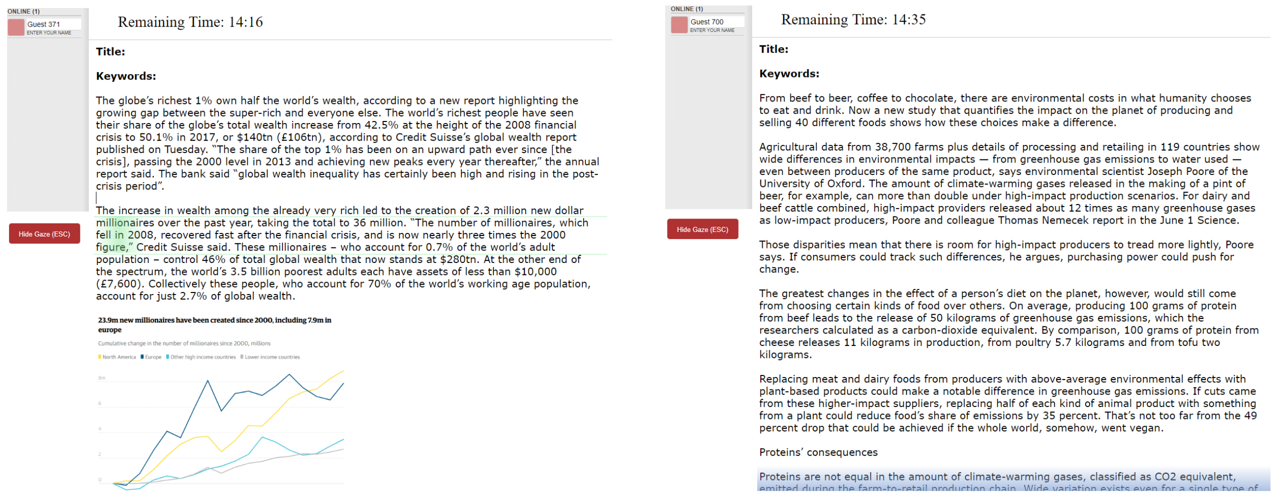


Figure 3: Eye-Write visualizes the co-author's point of gaze. The visualization can be deactivated at any point using a button or a key. Left: A gradient visualization indicates the x-coordinate while the three closest text lines are enclosed by two horizontal lines. Right: A shaded bar at the bottom or at the top of the page shows when the co-author's gaze is outside the viewport.

of its distractiveness, visual attractiveness, and ease of use. Two pairs strongly preferred the gradient visualization due to its effectiveness in communicating information, while the third pair was indecisive between the gradient and circle designs. The circular visualization was considered jumpy and distracting and its range was found to be small. On the other hand, the block visualization was found to be large and uninformative for prose text; users could not locate the precise location of their co-author's gaze. Contrary to [10], the bar visualization that was found particularly effective in a code-developing setting was the least liked by our users who either ignored it or found it ineffective. We hypothesize that this can be attributed to the differences in the nature of writing code versus academic text. As opposed to code, conceptual ideas in academic text often flow over many lines and extend significantly on the x-axis. The gradient visualization (Figure 3-left), was found to be the most effective, striking a balance on the quantity of information being communicated.

Based on the feedback, we incorporated the gradient visualization into Eye-Write. We consider two gaze-sharing conditions: constant gaze and optional gaze. The first shares the gaze of a co-author at all times, while the second allows the at-will display of the co-author's gaze. This feature can be activated via a button on the left side of the screen or a keyboard shortcut. We included the optional gaze condition because while collaborative subtasks are conducive to using gaze sharing, it may be distracting during individual subtasks. When the gaze sharing is activated, authors are given an indication of when their gazes overlap by the visualization turning green. This is triggered when there is an overlap between the three lines that the authors are predicted to be gazing at, and the predicted x coordinates are within 100 pixels. When one's gaze falls outside of their partner's viewport, the co-author is given an indication of where they can scroll to find their partner's gaze, either at the top or bottom of the screen (Figure 3-right).

5 STUDY METHOD

We conducted a study to evaluate Eye-Write under the gaze and optional gaze visualization conditions versus the default no gaze sharing. The study was reviewed and approved by our institution's Human Subjects Protection Committee.

Apparatus

To simulate remote working environment, a Windows 10 computer with a HP Pavilion 27-inch monitor (1920px by 1080px) and a Tobii 4C eye tracker with a sampling rate of 90Hz was placed in front of each participant. Participants were provided with Mpow noise-cancelling headsets with microphones for Skype communication. Adjacent to each participant was a Canon VIXIA HF R50 camera for recording the study. Screen recordings were captured with OBS Studio.

Participants

Forty participants were recruited via university-wide mailing lists for undergraduate students. We chose to recruit college students with the assumption that they are already familiar with collaborative academic writing. The participants were split into 20 dyads that were either self-selected or paired by the experimenters. Twenty-six participants were female. Overall, 37 participants indicated that their age was between 18 and 24, two were 24–29 and one was 30–39 years old.

Thirty participants had prior experience with OCW tools. Out of these, 29 had used them in synchronous mode, with 14 having used them at least a few times over the past year and 50% of the time with one collaborator.

Experimental Design

Participants worked in pairs on three writing tasks. Each task had to be completed within 15 minutes and required them to read a 500-word news article on economics, technology, and healthy eating, accompanied by multiple figures. As a pair, they had to summarize the article in a paragraph of 8–10 lines, either by keeping excerpts of the text, or through original writing. Participants were asked to choose together one of the figures in the original article to accompany their summary. Individually but simultaneously, one of them had to come up with a title for the article while the other listed five keywords. Together, participants decided on the task division. These different subtasks allowed us to see how authors react when they have to collaborate or work individually.

Each pair was assigned to one of two conditions, *GON* or *NGO*, resulting to 10 dyads for each. *G* is the version of the system where the co-author's gaze is always shown. *O* is the optional-gaze version, and *N* is the version where no gaze visualization is shown at all. In both conditions, participants performed tasks with all three versions of the system. *NGO* (*GON*) began with a writing task using version *N* (*G*), followed by a task with version *G* (*O*), and lastly a task with version *O* (*N*). Version *G* always preceded version *O* so that users would become familiar with the presence of their co-author's gaze. This allowed us to truly gauge whether gaze sharing is a feature that users are likely to keep when given the opportunity to deactivate it, especially when working individually to create a title and keywords.

Procedure

At first, participants were introduced to each other, if needed. Once seated at their workspaces on opposite sides of the room, with their backs facing each other, they were provided with written consent forms. Upon consent, the camera and screen recordings were activated. Users were then asked to perform the default calibration process on the Tobii Eye Tracking Core Software. A Skype audio call was then set up between the dyad and users confirmed that they could hear each other clearly in the headsets. Having the dyad in the same room allowed the experimenter to easily track their progress, while the lack of any visual contact and the presence of noise-cancellation headphones simulated a remote environment. Figure 1 shows the experiment setup.

After being presented with the expectations of the task, a description of the system, and the gaze visualization condition, participants were given two minutes to test the interface with filler text. They were then presented with the article they would be summarizing and were given time to read it before commencing the task. The process was repeated for all three tasks with the three different visualization conditions. At the end of each task, participants answered to an individual questionnaire inquiring about the quality of collaboration as they perceived it. At the end of versions *G* and *O*, the questionnaire included 12 questions of the Perceived Usefulness and Ease of Use Survey [13], in which participants could indicate their level of satisfaction with the gaze visualization tool. The experiment was concluded with a brief interview where participants discussed the gaze visualization with each other. Each participant received a compensation of 20 USD.

6 RESULTS

We collected data on the following measures: level of collaboration, deactivation of gaze sharing, quality of the collaboration process, and task completion time. We also analyze the post-experiment interview responses.

First, we examine the effects of shared gaze on the collaborative writing process in terms of the level and quality of collaboration. Previous studies have shown that pairs acknowledge deictic references successfully more often in the presence of gaze visualization [10]. This indicates that shared gaze is useful for fluid coordination and we expect that gaze visualization leads co-authors to spend more time on higher levels of work-coupling. In addition to the empirical findings, we aim to look at the perceived satisfaction of the writing partners with their collaborative writing process.

Second, we are interested in how mutually-shared gaze affects the task performance of a dyad. When co-authors are able to see the location of their partner's gaze, we would expect them to have increased situation awareness and conversational grounding. As with collaborative physical tasks [21], we hypothesize that pairs sharing more visual information should be able to complete the task faster since they are able to coordinate more efficiently. However, previous studies have not confirmed nor disproved this proposition [10]. It is equally possible that writers spend more time due to excess of visual information or more involved communication.

Level of Collaboration

The level of collaboration measure was based on the awareness evaluation model developed by Neale et al. [34] which divides the level of work-coupling into six stages of decreasing collaboration: cooperation, collaboration, coordination, information sharing, lightweight interactions, and no interactions. Table 1 provides an interpretation for each level.

Two independent raters agreed upon parameters for the six distinct levels of collaboration and coded the screen recordings of the 20 dyads using the BORIS software. Each second of each task was given a label corresponding to a

Level of Collaboration	Interpretation
1 - Cooperation	Partners have shared goals, common plans, shared tasks, and significant consultation with each other about how to proceed with the work.
2 - Collaboration	Participants perform separate tasks that have a high degree of interdependence, but work is still done by individual members.
3 - Coordination	Planning, scheduling, assembling resources, managing resources, task allocation, monitoring task, and activity states.
4 - Information sharing	Participants quote the text or share their own knowledge.
5 - Lightweight interactions	Causal social interaction, sharing of contextual information that is not specific to communication about the work.
6 - No interactions	Both participants are working separately; no communication.

Table 1: The six levels of collaboration, in decreasing order of work-coupling, as defined by Meier et al. [32]

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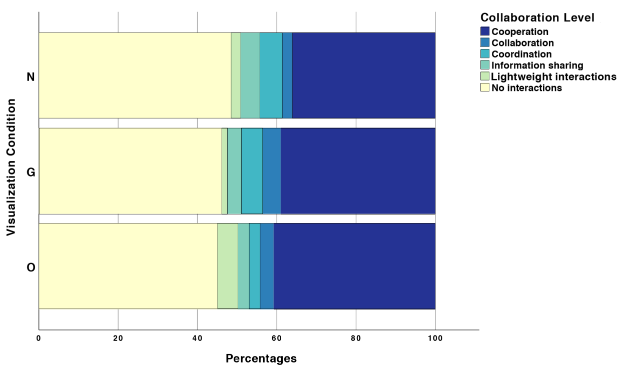

Figure 4: The percentage distribution of the six collaboration levels across the three different visualization conditions. Participants during conditions *G* and *O* exhibited higher levels of collaboration.

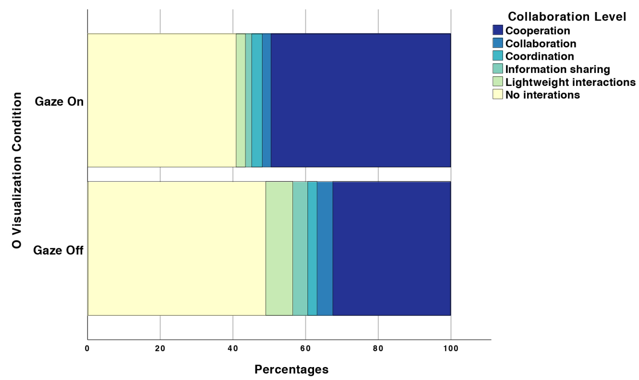

Figure 5: The distribution of the six collaboration levels during the *O* visualization condition. Bottom: the 10 dyads which who deactivated gaze-sharing for the entire task. Top: the remaining 10 dyads who kept the gaze-sharing feature on exhibited higher levels of collaboration.

collaboration level. For example, *Cooperation* was assigned when one co-author typed a sentence while the other verbally approved or gave suggestions, whereas *No Interactions* was assigned when co-authors worked on separate sections of the document without speaking for several seconds. A Cohen's Kappa value was calculated separately for each pair to summarize the agreement/disagreement per second, which resulted in a minimum value of 0.697 and a maximum of 0.925 ($M = 0.813$, $SD = 0.069$). The raters then discussed and resolved any disagreements and concluded to a final set of labels per second for all 20 recordings.

Figure 4 shows the percentage distribution of the six collaboration levels across the three different visualization conditions. A Pearson chi-square test showed a significant association between the visualization condition and collaboration level ($\chi^2(10) = 754.5, P < 0.05$). We followed with a Bonferroni-corrected post hoc analysis with adjusted residuals for all conditions and report some characteristic examples that overall show that *G* and *O* led to higher levels of collaboration than *N*. For example, the highest level of work-coupling, *Cooperation*, is found in 36% of the labels for *N* ($\chi^2(1) = 82.81, P < 0.002$), in contrast to 39% for *G* and 41% for *O* ($\chi^2(1) = 90.25, P < 0.002$). Similarly, the lowest level, *No interactions*, drops from 48% for *N* ($\chi^2(1) = 43.56, P < 0.002$) to 46% for *G* and 44% for *O* ($\chi^2(1) = 40.96, P < 0.002$). Similar trends were observed across all levels. These findings provide strong evidence for H1, on gaze sharing increasing the level of collaboration. Since *O* contains dyads that deactivated the gaze-sharing, we further look into this condition.

Optional Gaze

While analyzing the videos, we measured the use of the optional gaze feature during *O* by marking each occasion when a participant used either the button "Show/Hide Gaze" or the Esc key. Out of the 40 participants, 18 activated this feature, even if momentarily, and 12 deactivated the gaze visualization for the duration of the task under the *O* condition.

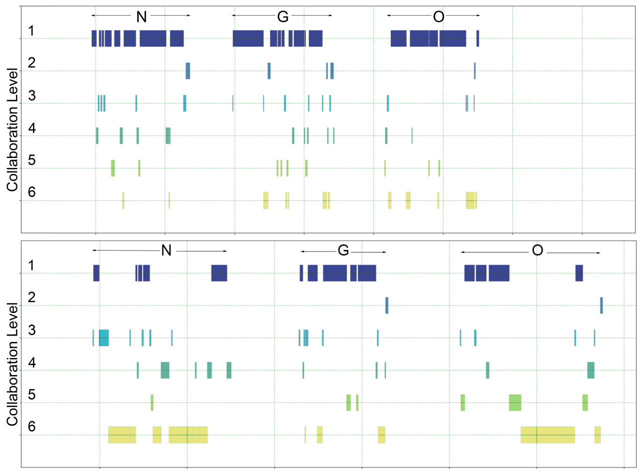

Figure 6: Collaboration level labels for two dyads that both underwent the *NGO* condition. Top: the dyad kept the gaze sharing feature on during *O*. *Cooperation* was the dominant level across all tasks. Bottom: the dyad deactivated the gaze sharing feature during *O*. Gaze sharing during *G* increased the level of collaboration compared to conditions *N* and *O*.

As a next step, we separated the 20 dyads into those with at least one author who deactivated the gaze-sharing feature (Gaze Off) for the entire task and those who did not (Gaze On). Figure 5 shows the percentage distribution of the six collaboration levels. A Pearson chi-square test showed that keeping the gaze on or off had a statistically significant association with the collaboration level ($\chi^2(5) = 586.90, P < 0.05$). A post hoc analysis with adjusted residuals and Bonferroni correction followed. The highest level of work-coupling, *Cooperation*, was reported at 50% of all labels for dyads that kept gaze sharing on, in contrast to 33% for those who deactivated it ($\chi^2(1) = 428.49, P < 0.004$). Similarly, the lowest level of work-coupling, *No interactions*, was reported at 41% and 49%, respectively ($\chi^2(1) = 94.09, P < 0.004$). This result provides further evidence for H1 and strengthens our argument that co-authors using gaze-sharing are more likely to engage in higher levels of work-coupling. It is worth noting that we do not argue that tighter work-coupling equates higher quality of collaboration. For example, working separately could imply higher levels of trust among the co-authors.

Figure 6 presents the labeling of collaboration levels for two dyads that both completed the study under the *NGO* condition. The top dyad kept the gaze-sharing feature on during the *O* condition, and consistently spent the majority of time in the *Cooperation* level. In contrast, the bottom dyad deactivated the gaze feature. Although, in general, most of the time was spent in the *No interactions* level, the dyad shifted to the *Cooperation* level under *G*. Their level of collaboration dropped again in *O* when they deactivated the gaze.

Quality of Collaboration

H2 assumes that the perceived quality of the collaboration process is higher when the gaze sharing feature is on. We evaluated the quality based on the participants' responses to the questionnaire at the end of each task. The questionnaire was created according to the rating scheme developed by Meier, Spada, and Rummel [32], which encompasses the nine dimensions of computer-supported collaboration (sustaining mutual understanding, dialogue management, information pooling, reaching consensus, task division, time management, technical coordination, reciprocal interaction, and individual task orientation).

Friedman's two-way ANOVA tests were applied on the three post-task questionnaire responses. The questions with statistically significantly different scores across the three gaze visualization conditions, followed by Dunn-Bonferroni corrected post hoc tests were: "Me and my partner sustained mutual understanding" ($\chi^2(2) = 21.81, P < 0.05$, for rank scores of 1.7 and 2.7 for *N* and *O*), "Me and my partner maintained joint attention" ($\chi^2(2) = 31.97, P < 0.05$, for rank scores of 1.61, 1.93, 2.46 for *N*, *G*, and *O*), "Me and my partner maintained smooth 'flow' of communication" ($\chi^2(2) = 24.13, P < 0.05$, for rank scores of 1.68 and 2.24 for *N* and *O*), "Me and my partner evaluated arguments for and against the available options" ($\chi^2(2) = 15.31, P < 0.05$, for rank scores of 1.7 and 2.26 for *N* and *O*), and "I was aware of my partner's activity" ($\chi^2(2) = 41.86, P = 0.001$, for rank scores of 1.44 and 2.39, and 2.17 for *N*, *G*, and *O*). These results support H2 by showing that gaze sharing increased certain aspects of the perceived quality of collaboration.

Feedback on Gaze Sharing

At the end of *G* and *O*, we solicited feedback on the gaze-sharing feature. The most positive aspects were: 1) it improves coordination by providing an overview of the writing partner's activity and thought process, even without verbal communication, 2) it aids collaboration by allowing co-authors to communicate about specific parts of the text, thus making referencing easier, 3) it enhances awareness of the writing partner and encourages maintaining joint attention, particularly during collaborative proofreading, and 4) it is an innovative tool that makes writing more engaging.

The concerns were: 1) the visualization is distracting due to its frequent movement, leading to difficulties in focusing on individual work, 2) its accuracy, since at times the eye tracker does not detect the user's gaze, and the confusion it causes when the writing partner is looking away from the screen, 3) the user's increased self-consciousness, causing nervousness and raising privacy concerns, and 4) the need for instructions on how the tool works.

A Wilcoxon signed rank test showed a statistically significant increase in the scores given to the gaze visualization between *G* and *O* for the "Perceived Usefulness and Ease of Use Survey" questions related to efficiency ($Z = 2.68, P = 0.007$), performance ($Z = 2.85, P = 0.004$), productivity ($Z = 2.06, P = 0.039$), lack of distractiveness ($Z = 2.83, P = 0.05$), learnability ($Z = 2.30, P = 0.021$), ease of operation ($Z = 4.26, P < 0.05$), flexibility ($Z = 4.16, P < 0.05$), ease to become skillful ($Z = 4.06, P < 0.05$) and use ($Z = 2.71, P < 0.05$).

Interestingly, the number of participants who found the visualization distracting decreased from 24 in *G* to 16 in *O* condition. This could have been due to participants deactivating the feature. However, the responses to open-ended questions revealed that many participants felt less distracted and more comfortable with the tool during *O*, since over time it became easier to use the gaze visualization. As one participant explained: "It is an effective tool but does require more training time from the user in order to take full advantage of it." We can infer that using gaze visualization involves a learning curve which, over time, allows users to become used to its visual presence while benefiting their writing.

The feedback following *O* showed that most participants who deactivate the gaze sharing did so because they found the gaze distracting (52%) and/or they wanted to better focus on their own portion of the task (48%). Those who did not deactivate the gaze explained their choice by saying that they liked to see where their partner was looking at (53%) and/or they did not feel the need to hide the gaze (53%). Four participants forgot about the gaze deactivation option. Finally, we asked for the participants' opinions on the possibility of choosing when the gaze visualization is shown. Among the majority of respondents who liked having the option (90%) were many who personally preferred keeping the visualization activated at all times but recognized that others might get easily distracted and thus found the optional feature necessary. These responses support our argument that at-will gaze sharing serves its purpose of accommodating writers' different working styles and preferences.

Completion Time

Contrary to H3, a one-way ANOVA with repeated measures did not show any statistical significant difference in the average completion time across the three different visualization conditions ($F(2, 38) = 1.188, P = 0.316$), and the task completion time under *N* was slightly lower (691 sec) compared to *G* (748 sec) and *O* (713 sec).

Post-Experiment Interview

The post-experiment interviews were conducted in a conversational format where participants discussed their writing experience and the different gaze conditions. The comments were coded and categorized as positive, negative or neutral. Each participant was assigned an "overall attitude" based on the category with the most comments.

The discussions between partners at the end of the experiment showed that most participants had a positive attitude toward the gaze visualization. Many participants explained how their partner's gaze was a good indication of their thought-process and/or activity, and therefore allowed to better coordinate the writing. For example, one participant mentioned: "It's easier to see what you are going through, so in the end, I could see you scan the whole paragraph, so I was like 'OK, she is checking to make sure we have a good summary'. It is a lot easier to reference what the other person is doing. Think about just having a more tangible idea and knowing that the other person is watching you."

Half of the participants in the *GON* condition missed the gaze visualization during the last writing task when they could not see their partner's gaze. This highlights the usefulness of gaze sharing in collaborative writing – dyads under *NGO* could not experience the lack of gaze sharing during *N*. Because of the time it took for the participants to get used to the constant movement of the visualization on the screen, many participants said they only realized the usefulness of the gaze when they no longer had access to it.

The interviews revealed that participants appreciated the at-will gaze sharing during *O*. Those who generally liked the gaze visualization explained that during individual work, the optional gaze enabled them either to continue using the gaze-sharing system or to deactivate the visualization while focusing on their portion of the text. Participants who found the visualization distracting said the option of permanently turning it off enabled them to avoid excessive visual information. One participant mentioned: "It was nice to have the show or hide [button] because there were some parts where the gaze became too cluttered for me, especially when I had to reread a paragraph. I liked the option of hiding it when I needed to, when I needed to read that specific thing, and then reconnect if I needed to see where you are looking at."

The reception of the gaze visualization varied largely even within a pair. For example, when one participant explained that they did not see its usefulness since they could communicate through voice, their partner responded: "I really liked it. It was cool cause when you were going to look for information, I could go and track where you were looking. I was a fan." These contrasting viewpoints underline the importance of flexibility that is provided to the writers by the at-will gaze sharing. As one participant concluded: "I liked the optional one 'cause then the person has a choice."

7 DISCUSSION

Our findings demonstrate the benefits of gaze sharing on collaborative writing and provide evidence for the positive effect of real-time mutual gaze visualization on the level of collaboration and perceived quality in remote settings.

Our work extends the existing literature in several aspects. While improvements in experimental setups with multiple eye trackers and independent viewports have been suggested [38, 43], no study to our knowledge has implemented such a system for remote document editing. Our research showed one possible way of conducting experiments with such a setup. Contrary to suggestions from previous research [10], our testing of different designs revealed that the left-aligned gaze visualization preferred by pair programmers would not provide sufficient support for co-authors in a writing task. Our gradient visualization is an example of how collaborative gaze-sharing tools need to be designed to account for the specific task characteristics. In addition, findings from the experiments with at-will gaze visualization indicated that future OCW tools should consider gaze sharing as an optional feature to accommodate writers' personal preferences as well as different collaboration styles.

Considerations

Participants had only 30 minutes in total to collaborate under the *G* and *O* conditions. This might have affected the results by magnifying distractions during the collaboration. However, the limited time might have caused other participants to provide positive feedback due to their initial excitement about the novelty of the tool.

Similarly, some pairs knew each other beforehand and were more comfortable with working together. Since collaborative writing is more likely to happen among writers who know each other, some of our findings could be attributed to the lack of prior familiarity with the person rather than the impact of gaze sharing itself. On the other hand, increasing familiarity with the nature of the experiment could lead to lowering levels of collaboration in each subsequent task, as dyads established strategies for approaching the tasks.

When designing this study, we focused on the *NGO* and *GON* conditions to account for the novelty of gaze visualization and the limited time of the experiment. During pilot testing, it became clear that we could not expect participants to make an informed choice about deactivating the gaze-sharing feature if they had not already established their preferences. Therefore, we excluded all combinations of the three versions that could have *O* precede *G*.

We focused on academic writing to limit the number of possible forms that collaborative writing may take. Our thinking was that academics often work under deadlines that impose word and page limits, and therefore are likely to collaborate *synchronously*. Collaborative writing contains multiple phases, with not all of them being synchronous. In such a case, the gaze sharing feature would not be useful. We recruited mostly undergraduate students as they are already familiar with academic writing and have a higher likelihood of having been exposed to OCWs [41].

Open Research Questions

Many participants mentioned that the gaze visualization would have been more helpful if there had not been any audio communication: "If we didn't have the headset, it would have been a lot more difficult to communicate and the gaze would have helped a lot more." We chose a Skype call as it simplified the problem we solved while allowing us to record and directly observe the verbal communication.

Intentionality was an important theme when we designed Eye-Write. We chose to have users explicitly decide when they would see their co-author's gaze but we envision this taking different forms. For example, speech recognition could be used to automatically detect when gaze should be shared.

Eye-Write in principle can support an arbitrary number of users. Here, we focused on dyads as the presence of more users raises different questions. For example, it is unclear if the gaze of all writers should be simultaneously visualized and what is the upper limit before it becomes distracting from the goal of writing. We imagine that as larger groups of collaborators become more common, there will be a need for further investigation of collaborative gaze sharing.

8 CONCLUSION

In this paper, we studied the effect of gaze sharing on synchronous collaborative writing in a remote setting. To this end, we built Eye-Write, a novel gaze-sharing system that allows two co-authors to use the gaze visualization at will while writing together. We used Eye-Write to conduct a study on academic collaborative writing with 20 dyads that were exposed to different gaze visualization conditions.

We discovered that gaze sharing during collaborative writing tasks increases the level of collaboration and leads to tighter work-coupling. In addition, shared gaze increases the perceived level of quality of collaboration, with participants reporting an increase in the level of mutual understanding, joint attention, flow of communication, level of negotiation, and awareness of each other's activity.

Gaze sharing offers unique insights into the process of collaborative writing by bringing out the visual aspect of writing together. The positive feedback to our at-will gaze-sharing system highlights the importance of accommodating different user preferences as a key aspect in developing future computer-supported collaboration tools.

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