How Learners Use Awareness Cues About Their Peer's Knowledge? Insights from Synchronized Eye-Tracking Data

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Abstract: In an empirical study, eye-gaze patterns of pairs of students were recorded and analyzed in a remote situation where they had to build a concept map collaboratively. They were provided (or not), with a knowledge awareness tool that provided learner A with learner B's level of knowledge measured through a pre-test. Previous results showed that the awareness tool positively affected learning gain by enhancing the production of elaborative talk and knowledge negotiation. In the present paper, we describe the actual use of a knowledge awareness tool during the course of interaction by analyzing the gaze paths recorded during the experiment and how they relate to learning performance and verbal interactions. The results showed that learners refer to the knowledge awareness tool episodically during the course of collaboration, mainly to assess the epistemic value of the information provided by the peer, especially when the peer seems uncertain about his understanding. The potential of the synchronized eye-tracking method for research in computer supported collaborative learning is discussed.

Introduction

In a large empirical study (Sangin, Molinari, Dillenbourg, Nüssli, 2007), participants learning in dyads were provided with cues about their partner's prior knowledge of a particular topic through what we refer to as a Knowledge Awareness Tool (KAT hereafter). The results of this study are summarized below. This contribution aims at deepening these results by exploring the way learners used the KAT information during the course of collaboration. We used two eye-tracking devices to record peers' eye-gaze data during the collaboration sessions. We report and discuss analyses of the eye-gaze data regarding the use of the KAT, and their relation with learning outcomes and verbal interactions. The potential of synchronized eye-tracking data for research in computer supported collaborative learning is discussed in light of the results.

Knowledge Awareness in Collaborative Learning

The role of social interaction in the development of knowledge is now broadly admitted by educational researchers (Wertsch, 1978; Slavin, 1983; Palincsar, 1998). According to Dillenbourg (1999), learners benefit from collaboration because they produce interactions such as explanation (Jeong, 1998), argumentation (Baker, 1994), mutual-regulation (Blaye, 1988) or conflict resolution (Doise & Mugny, 1984). The extent to which these verbal interactions between peers lead to elaboration of new knowledge depends on the quality of these interactions. Roschelle and Teasley (1995) summarized this set of interactions as the process of building and maintaining a shared understanding of the task learners are involved in. Many CSCL researchers have since been inspired by psycholinguistic concepts such as "shared knowledge" or "common ground" (Clark & Brennan, 1991). Grounding is the process through which individuals engaged in a conversation try to ensure their mutual understanding.

In order to build a common ground and make the communicative process effective, learners must have some representation of their partner (Clark 1996; Clark & Murphy, 1982). We refer to the process of building a representation of the partner(s) beliefs, knowledge and intentions as mutual modeling (Dillenbourg, 1999; Sangin, Nova, Molinari & Dillenbourg, 2007). A growing body of literature highlights the importance of knowing what the partner knows and does not know for speakers (Clark & Marshall, 1981; Krauss & Fussell, 1991; Nickerson, 1999, Schober, 1998). For Krauss and Fussell (1991), speakers formulate their messages in order to be understood by the audience. They argue that this process of "perspective taking" is necessarily probabilistic and that there is no simple mechanism to identify with certainty what is mutually known (Krauss and Fussell, 1991). The communicators draw on two distinct sources of information to formulate their messages, the inferred prior knowledge and the current feedback, which are dynamically related and feed each other.

In the same line of research, studies showed that people are biased in the direction of their own knowledge when estimating the audience's knowledge (Steedman & Johnson-Laird, 1980, Nickerson, 1999; Chi et al., 2004; Bromme, Jucks, Runde, 2005). More knowledgeable people are more likely to overestimate the audience's knowledge while those who are less-knowledgeable tend to underestimate it. Misunderstandings occur when the speaker holds false beliefs about the listener's knowledge. Overestimating the attendee's knowledge may produce explanations that are too difficult to understand while underestimating a partner's knowledge may lead the speakers to provide information that is already known (Wittwer, Knückles, Renkl, in press).

Consequently, these considerations are central to collaborative learning situations where peers build upon each other's knowledge and learn through mutual appropriation of knowledge and skills (King, 1998). Holding an accurate model of the partner's knowledge may help co-learners to provide explanations on an appropriate level of elaboration. We do not claim that students permanently maintain an explicit and detailed model of their partner's knowledge, but rather that some correct representation of the partner smoothes collaborative processes. In the domain of Computer Supported Collaborative Learning (CSCL), some researchers proposed to provide learners with tools that enhanced their awareness of the partner's knowledge. Ogata and Yano (2000) proposed the notion of knowledge awareness to increase collaboration opportunities of shared knowledge construction in an open ended collaborative learning environment. More recently, Leinonen and Järvelä (2006) proposed a visualization tool as a knowledge externalization aiming at supporting the interpersonal evaluation of knowledge and showed its positive effect on group performances. To sum up, providing learners with an external help that allows them to accurately assess the partner(s) knowledge has the great potential to trigger germane socio-cognitive processes that by extension may enhance collaborative learning performances.

Goal and research questions:

Our experimental study investigated whether providing learners with cues about their partner's prior knowledge affects the learning performances in distant collaborative learning tasks (Sangin et al., 2007). This contribution does not report the basic results but provides new analyses obtained by using two eye tracking machines. We nonetheless summarize the main results here:

1. Learners provided with cues about their peer's knowledge during the collaboration obtained a significantly higher learning gain than participants who were not provided with these cues.
2. This effect was (statistically) mediated by the fact that the Knowledge Awareness Tool (KAT) enhanced participants' accuracy in estimating their partner's knowledge.
3. Analyses of verbal interaction showed that the KAT increased the production of elaborated "information providing" utterances, which were positively and significantly related to learning gains. The KAT also enhanced exploratory talk (Mercer, 1996) about conceptual knowledge.

The obvious interpretation of these results is that information about the partner's knowledge allows learners to build a more accurate model of their partner's knowledge. This model serves as basis for audience design (Clark & Murphy, 1982), perspective taking (Krauss & Fussell, 1991) and making processes that benefit communication efficiency and ultimately enhance the collaborative learning gain. However, these results also raise at least one additional question: How did the participants use the information provided by the KAT? The present paper is aimed at providing an answer to this new question by analyzing the actual use the learners made of the Knowledge Awareness Tool. In order to do this, we analyzed the eye-gaze data recorded during the collaboration in order to address the following sub-questions:

A) When do the learners consult the KAT? Do they look at it once at the beginning or do they refer to it episodically during the course of interaction?
B) Is there a relation between the amount of time spent consulting the KAT and respectively the learning outcomes and the accuracy in estimations of the partner's knowledge?
C) Do the participants look at the KAT during specific moments and what are these moments?

Method

Participants and design:

Sixty-four first year students (18 women and 46 men, mean age = 21.2 years) of the Swiss Federal Institute of Technology in Lausanne participated in the study. They were involved in curricula that did not involve advanced neurophysiologic notions and had basic but sufficient knowledge about how to use computers. They were randomly assigned to 32 dyads. Sixteen dyads were assigned to each of the two following conditions: (1) experimental (KAT) condition, in which the participants were provided with the Knowledge Awareness Tool; (2) control condition, in which they were not provided with the KAT. Peers did not know each other before the experiment. Students were remunerated 30 Swiss Francs for their participation.

Instructional Material and Apparatus

Instructional Material. The Instructional Material consisted of an explanatory text about the neurophysiologic phenomenon of "action potential" written with the help of domain experts (a neurobiology researcher and a biology teacher). The text was divided into 3 chapters: "the resting potential", "the initiation of the action potential" and "the propagation of the action potential".

Apparatus. We developed an automated experimental setup running on two computers connected to two eye-tracking screens (Tobii™ 1750) distributed in two different rooms. The experimental setup allowed us to automate all the procedure (i.e. learning phases and tests). During the collaborative phase, participants used an on-line concept-map building software (CmapTools, IHMC). They were provided with a microphone-headset during this phase in order to communicate with each other and their verbal interactions were recorded.

Procedure and scoring

Each partner was located in separate rooms, in front of two eye-tracking setups running the automated experimental setup. The experimental session lasted for approximately 90 minutes and consisted of 6 phases, the main phases being individual reading (2) and collaborative concept mapping (4):

(1) First, the participants' prior knowledge of the instructional material was tested through an open-question in order to detect potential experts of the domain.
(2) During the *individual reading phase,* participants were asked to carefully read the instructional texts during 12 minutes. The three chapters were freely accessible in any order.
(3) A pre-test (*test1*) was administrated. It consisted of 30 items: two multiple-choice questions and eight inference verifications for each of the three chapters. The multiple-choice questions included four possibilities with one or more possible correct answers. The minimum score for these items was 0 and the maximum 4. The inference verification items consisted of true or false assertions. The score was 0 for incorrect answers and 1 for correct answers. The *test1's* overall range was 0 to 48 (0 to 16 for each chapter). All items were validated by experts of the domain and their variability was tested in a pilot study.
(4) Participants were provided with instructions about the collaborative phase and with a short video tutorial on how to use the CmapTools© interface. Then they had 20 minutes to draw a collaborative concept-map describing the content of the texts. They were able to communicate orally through headsets. The participants of the experimental condition were provided with the *KAT* on the bottom part of the screen (see Figure 1): it represented the partner's pre-test scores on each chapter. Participants of the control condition were not provided with the *KAT*. During this phase, the two peers' on-screen eye-gaze movements were recorded.
(5) The post-test (*test2*) was administrated including the same items than the pre-test but in a different order.
(6) Finally, participants were asked to estimate their partner's knowledge at the post-test for each of the three chapters on a 7-point likert-like survey.

The *Relative Learning Gain (RLG)* was computed for each chapter as the different between the post-test and pre-test score divided by the difference between the pretest score and the maximal score. The total RLG was obtained by calculating the mean of the RLG of the three chapters. The accuracy of participants in estimating their partner's knowledge was computed by taking, for each chapter, the absolute value of the difference between the A's estimation of B's knowledge, and the B's score on the *test2*. The total estimation accuracy score was the mean of the three chapters (for more details, see Sangin et al., 2007).

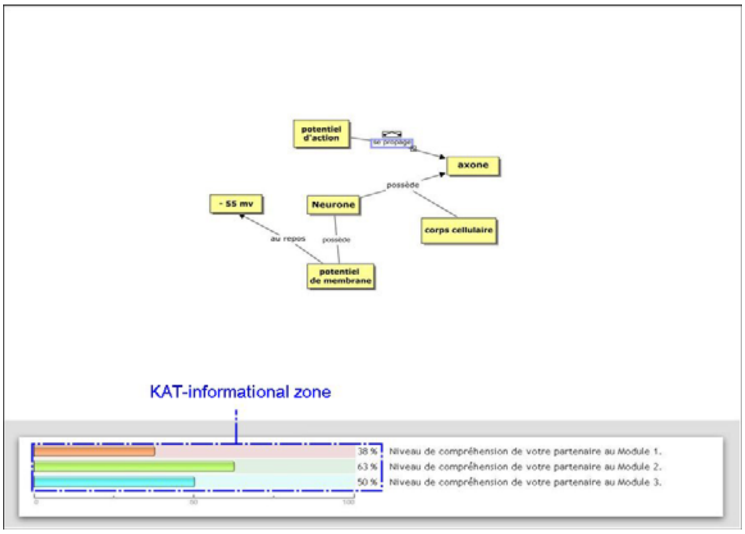


Figure 1. Screenshot of the KAT condition during the concept-map building phase.

Coding of verbal interaction:

Verbal interactions were recorded and transcribed verbatim. In order to test our hypotheses about the quality of interaction, we used a quantitative content analysis method (Strijbos, Martens, Prins & Jochems, 2006). The segmentation and coding were separated in order to enhance the precision. Utterances were used as unit of analysis. An utterance is defined as a "unit of meaning" (Neuman, Webb & Cochrane, 1995) of conceptual understanding. The reliability of segmentation and coding was computed by using the proportion of agreement between two independent judges on 13% of the corpus. The level of agreement reached 86%. The coding scheme was developed in order to focus on the following aspects of the verbalization: elaborative information seeking and providing, elaboration of conflict, knowledge negotiation and mutual-regulation (see table 1). This paper reports results on aggregated relevant coding categories.

Table 1: Mutually exclusive coding categories of peers' interaction.

	category	code	Description
Content-related categories	Information Providing	IP	Utterances where the speaker provides new information about the content in the form of statements or concept-map improvements.
	Information seeking	IS	Utterances where the speaker asks for new information or asks for validation of a certain piece of domain-related information.
	Contradicting	CT	Utterances where the speaker explicitly contradicts his partner by providing an alternative piece of information.
Non-content-related categories	Collaboration management	CM	Utterances related to the strategic management of the task (i.e. concept-map building) and the interaction (i.e. turn-taking)
	Knowledge Cues	KC	Utterances where the speaker provides a cue about the quality of his knowledge and understanding
	KAT Reference	Kref	Utterances with an explicit reference to the KAT
	Others	OT	Utterances which did not fit the previous categories (e.g off-task, repetitions, incomplete sentences etc.).

Eye-gaze data collection:

The eye-gaze data was gathered using two eye-tracking screens (Tobii© 1750) connected to two identical computer setups. The eye-movements of each peer were recorded during the 20 minutes of the collaborative concept-map building phase. For each dyad, the two sets of gaze data and the coded interactions were computationally synchronized with less than 30ms lag (the maximum delay offset tolerated). We used computational scripts to compute the amount of gaze-data falling in the KAT informational zone (see figure 1) for the learners in the KAT condition. KAT-episodes, during which the learners were looking at the KAT information, were also automatically detected. A sequence was considered a KAT-episode when at least 20% of the eye-gazes fell on the KAT zone during at least 2 sec. Each KAT-episode lasted as long as the amount of eye-gaze data falling in the zone represented more than 20% of the overall gaze-data. We detected an overall of 106 KAT-episodes with a minimum duration of 2 sec, maximum duration of 154 sec and a mean duration of 8.2 sec.

As the present paper is aimed at assessing the actual use of the KAT, only the KAT-condition dyads were considered for the following analyses. Due to technical issues regarding gaze records (e.g. missing data, lack of quality in eye-gaze data, synchronization issues etc.), five pairs were removed from the data reported here. Hence the reported results concern 10 pairs / 20 participants of the KAT condition.

Results

A. When do the learners look at the KAT?

When do the learners look at the KAT? Do they need it once at the beginning of the collaboration phase or do they refer to it during the course of the collaboration? To answer this question, we calculated the average ratio of eye-gaze falling in the KAT informational zone. Figure 2 represents this mean value plotted against time: the maximum peak is reached at the very beginning of the collaboration. As one can see, a large amount of gazes-on-KAT occur during the first 60 seconds of the collaboration. This corresponds to the moment when the KAT is first introduced (i.e. the beginning of the collaboration phase). However, the succession of subsequent smaller peaks suggests that learners also referred to awareness cues about their partner's knowledge more locally.

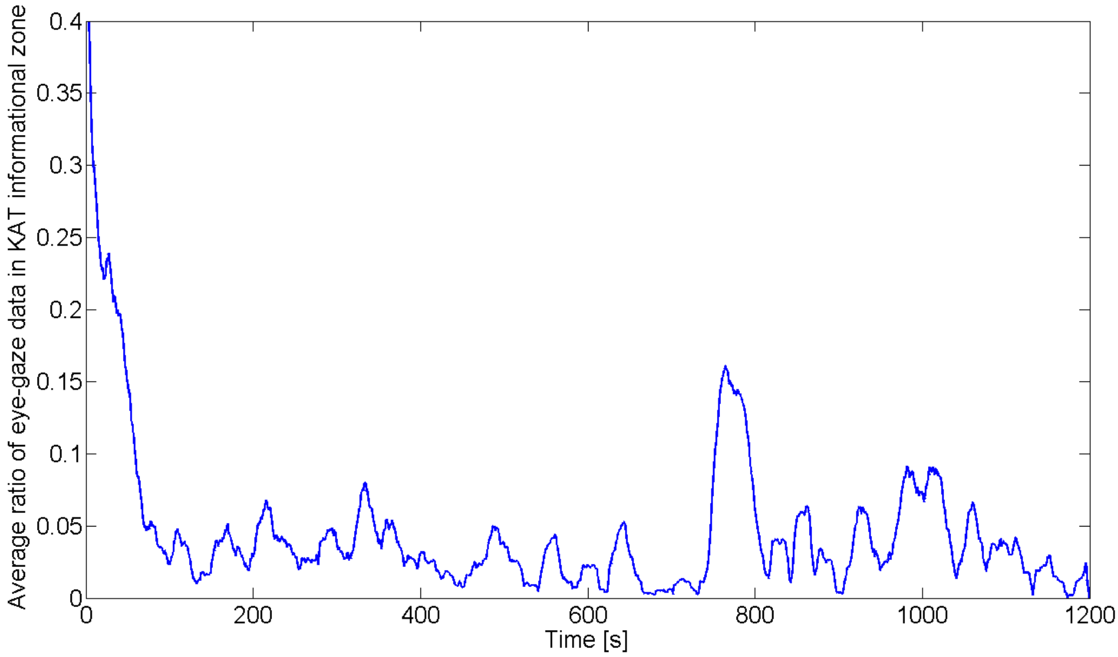


Figure 2. Means of eye-gaze data falling in the informational parts of KAT during the course of collaboration.

B. How is the use of the KAT related to learning outcomes?

We found a positive and significant correlation between the number of gazes-on-KAT and the learners relative learning gain ($r(20) = .54$, $p = .01$). This result suggests a rather high relation between the amount of time the learners spent consulting the KAT and their relative learning gain: the more they look at KAT, the more they seem to learn.

We also computed the correlation between the number of gazes-on-KAT and the accuracy in estimating the partner's knowledge. However, the correlation is not significant ($r(20) = .07$, *ns*). This lack of correlation can partly be explained by two outlier learners who spent considerably more time referring to the KAT than the rest of the participants. These learners belonged to the same dyad and intensively talked about the KAT during a relatively long episode (154 sec) which partly explains the second highest peak of Figure 2. However, despite these outlier learners, no significant conclusion can be drawn about a relation between the time spent looking at the KAT information and the accuracy in estimating the knowledge level of the partner.

C. Do learners consult the KAT on specific occasions?

We previously reported that learners consult the KAT on a regular basis during the course of collaboration. We explored qualitatively the episodes during which they actively consulted the KAT information by analyzing what types of utterances were produced during these episodes. Table 2 summarizes the amount and percentage of utterances of each type. The first row (All) reports the overall distribution of utterances of each type produced by the 20 participants in the KAT condition. The second row (KAT-episodes) reports the distribution of utterances of each type produced by both of the peers during KAT-episodes. The third row reports the utterances produced by the *KAT-viewer* during the KAT-episodes. By *KAT-viewer* we mean the learner whose gaze data was taken to detect the current episode. And finally, the fourth row reports utterances produced by the viewer's partner when the *KAT-viewer* was looking at the KAT.

We used Pearson's chi-square test to compare the distribution of utterances which occurred during KAT-episodes (KAT-episode) to the general distribution of overall utterances (All). The test reported that the two distributions were independent ($\chi^2 = 1193$, $p < .001$). A closer look at the residuals showed that the main differences in these two distributions come from the *Knowledge Cues* (*KC*), *Information Seeking* (*IS*) and *explicit reference to the KAT* (*KRef*) categories. Thus, this analysis shows that more of the KC, and *KRef* utterances and fewer of the IS utterances occurred during the KAT-episodes compared to the overall distribution of utterances.

Table 2: Overview of interaction results (Columns are coding categories listed in Table 1)

	IP	IS	CT	KC	CM	KRef	Other	total

All	494 *(30.9%)*	99 *(6.2%)*	55 *(3.2%)*	86 *(5.4%)*	259 *(24.9%)*	36 *(2.3%)*	322 *(27.2%)*	***1347 (100%)***
KAT-episodes	71 *(28.5%)*	8 *(3.2%)*	4 *(1.6%)*	35 *(14.1%)*	22 *(20.5%)*	30 *(12.1%)*	40 *(20.1%)*	***210 (100%)***
KAT-viewer	24 *(22.4%)*	5 *(4.7%)*	3 *(2.8%)*	13 *(12.2%)*	12 *(23.4%)*	15 *(14%)*	16 *(20.6%)*	***88 (100%)***
Viewer's Peer	47 *(33.1%)*	3 *(2.1%)*	1 *(0.7%)*	22 *(15.5%)*	10 *(18.3%)*	15 *(10.6%)*	24 *(19.7%)*	***122 (100%)***

We also compared the distribution of the utterances produced by the *KAT-viewers*' during episodes where they were consulting the KAT information, to the distribution of utterances produced by their peers. The Pearson's Chi-square test reported that these two distributions were also independent (χ^2 = 162.4, $p < .001$). A closer look to the residuals suggested that the differences are mainly explained by the *IP*, the *IS* and the *KC* categories. Indeed if we refer to the results presented in table 2, we can see that there are twice as many *Information Providing* utterances produced by the *viewer's peer* during KAT-episodes than by the viewer himself (47 vs. 24). This means that, there is twice the chance that learner A was looking at the KAT when the partner B was providing information than when A himself was providing new information. Furthermore, it appears that during the KAT-episodes, the *KAT-viewers* produced more Information Seeking utterances than their peers (5 vs. 3). These results also support the fact that there is more chance of having a *Knowledge Cue* provided by the KAT-viewer's peer occurring when the KAT-viewer is looking at the KAT information. Another interesting fact is that the KAT-viewers produced fewer utterances than their partners when they were consulting the KAT (88 vs. 122). In other words, when A was looking at the KAT, it is more likely that B was talking rather than A himself.

The following excerpts (translated from French) illustrate what happens during typical KAT-episodes. In these examples, the *viewer* is the learner who is consulting the KAT during the episode in question and the *peer* is his partner. The timelines of the utterances and the corresponding *viewer*'s fixations on the KAT are represented under each excerpt. The first line is the representation of the *viewer*'s utterances timeline, the second line represents the *peer*'s utterances timeline and the third line represents the *viewer*'s fixations timeline.

The first example is a typical KAT-episode occurring at the beginning of the collaboration where the learners discover the KAT, exchange each other's scores and talk about it. After exchanging their score represented in the KAT, the viewer says that she studied a little bit of biology during her past studies and it probably helped her performing on the pre-test [utterance (4)]. The viewer's peer reports never having studied that topic before.

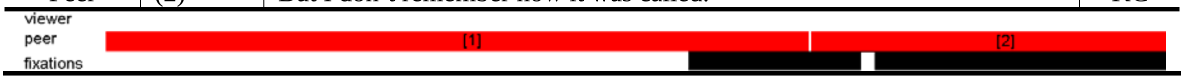
Example 1.

Speaker	N°	utterance	code
peer	(1)	Actually you have my scores.	Kref
viewer	(2)	OK you have 50-56-50	Kref
Peer	(3)	And you did 56-44-25 [laughing]	Kref
Viewer	(4)	Actually I did a little bit of biology in the past. It probably helps.	KC
Peer	(5)	Oh! .. Ok! Personally I almost never studied this.	KC

The second excerpt provides an example of a situation where the viewer's peer describes a phenomenon but is not able to remember the name. The *viewer* consults the KAT at that moment.

Example 2.

Speaker	N°	utterance	code
Peer	(1)	There was an ion's transportation in the channels … I mean it worked better when it was larger.	IP
Peer	(2)	But I don't remember how it was called.	KC



Discussion and conclusions

We used a new investigation method consisting of the synchronized eye-gaze data of pairs who learned collaboratively in a remote concept-map building task. Peers' eye-gaze data were synchronized with their verbal interaction to investigate the actual use they made of a Knowledge Awareness Tool that provided them with cues about their partner's knowledge. The first question we asked was whether the learners consult the information provided by the KAT only once or whether they refer to it on a regular base. This question is legitimate given the fact that the information provided by the KAT remains, after all, quite basic. Eye-movements allowed us to show that they consult the information episodically. It seems that learners do not use this information simply at the beginning to build a mental model of their partner but that they also refer to it when they need to update their model or to use it as grounding support.

The second question was whether the time spent consulting the KAT was related to learning performance. The amount of time spent looking at the KAT information was positively correlated to the collaborative learning gain. Even though no causal conclusion can be drawn, it is interesting to know that looking at the KAT is positively related to the collaborative learning gain. An even more intriguing result is the lack of correlation between the time-on-KAT and learners accuracy in estimating their partner's knowledge. Further analyses showed that this lack of relation is partly explained by outlier learners who spent considerably more time-on-KAT than the average population. Another explanation could be the rather low number of subjects available to compute the correlation. However, it is worth noting that the KAT information, i.e. the partner's score at the pre-test does not indicate the partners score at the post-test, since knowledge is expected to evolve during the collaboration.

Analyses of *gaze-on-KAT episodes* provided insights about the main situations where learners seem to refer to the KAT information. Obviously they refer to it broadly at the beginning when they exchange their scores and discuss about the strengths and weaknesses of each other's knowledge. More interestingly, they also refer to it when their partner provides verbal cues about the quality of their knowledge. It seems that during these moments of epistemic uncertainty, learners compare the verbal cues provided by the peer about his own knowledge and the information provided by the KAT. Furthermore, they also seem to consult the KAT significantly more when their partner is providing new information. Apparently in some situations, the KAT serves co-learners to assess the information provided by their partner. One of the main effects of the KAT seems to be the fact that it allows learners to become aware of epistemic uncertainty related to their understanding and allows them to deploy strategies to cope with it. It may also explain why participants of the KAT condition performed more knowledge negotiation (e.g. more exploratory talk) than participants of the control condition who were more focused on task completion aspects (e.g. more cumulative talk; Mercer, 1996).

Recent technological advances provided new, cheaper, faster and less constraining eye-tracking devices which fostered research efforts in Cognitive Science and Human-Computer Interaction to investigate cognitive processes and usability. However these investigations are restricted to individual settings. In this paper, we reported investigation where pair learners' eye-gaze data were used to analyze the collaboration process on a deeper level. Dual-eye-tracking method appears to be a new "window into the mind" of co-learners, and hence is of a great potential for CSCL research. It allows opportunities for more fine-grained analyzes of socio-cognitive processes such as grounding, mutual regulation and so forth. Many new opportunities to further our understanding of socio-cognitive processes such as shared visual attention (Richardson & Dale, 2005), referential breakdowns and conversational repairs (Cherubini et al., submitted) become possible, providing promising research perspectives.

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