



Communication facilitates focused monitoring and anticipation of critical events: evidence from eye movements

Catrin Hasse & Carmen Bruder

To cite this article: Catrin Hasse & Carmen Bruder (01 Oct 2026): Communication facilitates focused monitoring and anticipation of critical events: evidence from eye movements, *Ergonomics*, DOI: [10.1080/00140139.2026.2739574](https://doi.org/10.1080/00140139.2026.2739574)

To link to this article: <https://doi.org/10.1080/00140139.2026.2739574>



© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



Published online: 01 Oct 2026.



Submit your article to this journal [↗](#)



Article views: 162



View related articles [↗](#)



View Crossmark data [↗](#)

RESEARCH ARTICLE



Communication facilitates focused monitoring and anticipation of critical events: evidence from eye movements

Catrin Hasse and Carmen Bruder, Dr.

Department of Aviation and Space Psychology, German Aerospace Center (DLR), Institute of Aerospace Medicine, Hamburg, Germany

ABSTRACT

The present study investigates the impact of communication availability on monitoring behaviour in a team. A monitoring task was designed to compare participants who were not allowed to communicate with those allowed to communicate while monitoring an automated system and deciding repeatedly whether critical events would turn into failures. Four monitoring phases were distinguished around every critical event: identification, verification, anticipation, and detection. Eye-tracking parameters obtained during these phases were related to relevant areas of interest. Results show that the opportunity to communicate increases the proportion of attention on relevant events, particularly during anticipation, and leads to faster fixations on failures during detection.

Practitioner Summary: The mere opportunity to communicate primarily helps operators anticipate critical events and detect failures more quickly. These findings suggest that eye-tracking data can support workplace design, personnel selecting and training—particularly by fostering attentional readiness during the anticipation phase.

ARTICLE HISTORY

Received 20 May 2025
Accepted 21 September 2026

KEYWORDS

Automation; monitoring; eye tracking; communication; anticipation

Introduction

In aviation, team-based monitoring of automated processes is increasingly prominent. According to the Single European Sky ATM Research (SESAR) Programme, research on the future of aviation aims towards greater levels of automation. Such developments imply that the nature of human roles and tasks will necessarily change (SESAR JU, 2020; Single European Sky ATM Research 3 Joint Undertaking, 2024). With the introduction of highly automated systems, monitoring and teamwork will pose challenges (Bruder, Jörn, and Eißfeldt 2008; Svensson et al., 2021). Consequently, operators must effectively monitor the system, detect failures in a timely manner, and take control if automation fails (Eißfeldt et al. 2009; Eißfeldt and Gayraud 2015; Eißfeldt 2017). Furthermore, given that high-performing operational and technological systems are becoming increasingly complex (SESAR JU, 2020), it is conceivable that they should be monitored by teams (Hasse, Grasshoff, and Bruder 2014).

A control room is an example of a working environment where operators supervise complex and dynamic processes together. Control rooms are particularly prevalent in domains where safety is critically important, such as airport operational centres, air traffic

control centres, nuclear power plant control rooms, and military control centres, where human error can have severe consequences (Hauland 2008; Salas, Cooke, and Rosen 2008). As monitoring is one of the core tasks in control rooms, operators must appropriately monitor the system (Sharma et al., 2016). To meet such complex operational challenges, research emphasises the need to adapt personnel selection and training to the evolving demands of future aviation environments (Eaglestone et al. 2022; Wium & Eaglestone, 2022). In the case of monitoring automated systems, this specifically requires developing objective measures of monitoring performance and identifying conditions in which this performance improves.

Monitoring as an individual task

Based on previous work on monitoring as an individual task (e.g., Niessen and Eyferth 2001; Wickens et al., 2001), a normative model was derived (Hasse et al. 2009; Bruder et al. 2014), suggesting distinct phases within the entire monitoring process: orientation (at the beginning of a new situation), anticipation (during a critical situation in which the probability of a failure occurring is increased), detection (during the occurrence of a failure),

CONTACT Catrin Hasse  catrin.hasse@dlr.de  Department of Aviation and Space Psychology, German Aerospace Center (DLR), Institute of Aerospace Medicine, Sportallee 54A, 22335 Hamburg, Germany.

© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

and recheck (the time afterwards). Thus, appropriate monitoring requires operators to orient themselves towards automated system operations and to anticipate, detect, and recheck them in time (Hasse and Bruder 2015; Bruder and Hasse 2019, 2020).

Eye-tracking parameters

Eye movement data are widely used to reveal underlying perceptual and cognitive processes (Inhoff and Radach, 1998; Findlay and Gilchrist 2003; Holmqvist et al. 2011). In the context of human-automation interaction, eye movements have been instrumental in providing detailed insights into monitoring performance (Hasse and Bruder 2015; Bruder and Hasse 2020).

Research has consistently shown that effective operators gather relevant information via eye movements, enabling the detection of automation failures (Hasse, Grasshoff, and Bruder 2012b; Bruder and Hasse 2020) and subsequent manual control takeover (Hasse, Grasshoff, and Bruder 2012a; Hasse et al. 2013). Specifically, operators monitoring appropriately (OMA) are characterised by focusing on relevant information faster, more frequently, and for longer durations. This focus is quantified using eye-tracking parameters such as total times to first fixation (TTTFF), relative fixation counts (RFC), relative dwell times (RDT), and mean fixation durations (MFD) (Bruder and Hasse 2020). The RFC indicates attentional focus, interest, and expectation in terms of frequency (Rötting 2001; Jacob and Karn 2003; Poole and Ball 2006), whereas the RDT reflects the same psychological constructs in terms of duration (Friedman and Liebelt 1981; Pieters, Rosbergen, and Hartog 1996; Ryan and Cohen 2004). The MFD serves as an indicator of processing difficulty (Fitts, Jones, and Milton 1950; Just and Carpenter 1976) or depth (Velichkovsky, 2001; Pannasch 2003). The TTTFF can be used as a measure of the viewers' perceptual speed or activation potential (Byrne et al. 1999; Rötting 2001; Joos, Rötting, and Velichkovsky 2003). One study showed that when different eye movement parameters were combined in a model, failure detection could be predicted with an accuracy of 75.6% (Bruder and Hasse 2020). However, this predictability varies by phase; for example, monitoring adequately during anticipation and detection phases is more important for failure detection than monitoring adequately during recheck phases (Bruder and Hasse 2020). Relevant areas of interest (AOIs) are focused on even more in the anticipation phase than in the detection phase, in which all possible events are considered rather than just the directly relevant ones (Hasse and Bruder 2015).

The anticipatory guidance of attention, coupled with the prevalence of look-ahead fixations (Lehtonen et al. 2013; Pelz and Canosa, 2001), confirms that expectancy serves as the primary driver for visual monitoring of salient events in the traffic environment (Wickens et al., 2001). Barzantny (2024) notes that this phase is particularly critical for failure detection and thus a key target for training interventions.

Monitoring as a collaborative task: the influence of communication

In complex socio-technical systems, oral communication—the verbal exchange of information and ideas (Carvalho, Vidal, and Carvalho 2007)—is a key ergonomic resource and a “meta-teamwork process” (Papenfuss 2013). Traditional teamwork frameworks suggest that high-quality verbal exchange has been associated with the formation of Shared Mental Models (SMMs) (Andrews et al. 2023; Carraro, Furlan, and Netland 2025; Esmaeili et al. 2025) and the regulation of mental workload (MWL; Hasse, Grasshoff, and Bruder 2014; Li-Wang et al., 2023; Möhlenbrink et al., 2011). These communicative processes have been linked to systemic outcomes, including better failure detection, improved joint decision-making, and enhanced system safety (Bruder et al. 2019; Gorman, Cooke, and Winner 2006; Kim et al. 2024; Yeong & Shah Rollah, 2016).

However, from an ergonomic and design perspective, a more fundamental system decision must be addressed first: whether a communication channel should be enabled or restricted at all (Bednar and Welch 2020; Pöhler et al. 2025; Kusk, Nouwens, and Lee 2026). This baseline distinction is critical because introducing a communication channel is not a neutral system parameter; depending on task demands, it carries inherent trade-offs between collaborative support and potential distraction (Idaszak 1989; Brummelhuis, Hoeven, and Toniolo-Barrios 2021; Venkatesha Murthy et al., 2025).

To provide an empirical foundation for this system decision, the present study uses eye tracking to examine how the mere opportunity to communicate—regardless of its content—influences visual information acquisition. Using eye-movement metrics (TTTFF, RFC, RDT, MFD), which have been established in prior work as indicators of perceptual speed, attentional focus, sustained attention, and processing depth, respectively (Friedman and Liebelt 1981; Byrne et al. 1999; Jacob and Karn 2003; Pannasch 2003), we examine how the mere opportunity to communicate influences visual attention patterns.

Prior research has shown that rich communicative content enhances failure detection (Harrison et al. 2024; Dong and Li 2025) and that explicit verbal exchanges guide visual search towards critical cues (Kontogiannis and Malakis 2009; Niehorster et al. 2019). Applying this rationale to communicative availability, we hypothesise that the mere opportunity to communicate leads to shorter TTFF, reflecting faster visual attention allocation to failure-relevant events (Byrne et al. 1999; Rötting 2001; Joos, Rötting, and Velichkovsky 2003).

Moreover, while prior research demonstrates that rich verbal exchange provides attentional guidance and stabilises focus on task-relevant information to mitigate change blindness (Knott et al. 2007; Tollner-Burngasser et al. 2010), we assume that the mere opportunity to communicate exerts a comparable effect on visual attention. Specifically, we expect that the opportunity to communicate will lead to higher RFC, indicating heightened attentional focus (Rötting 2001; Jacob and Karn 2003; Poole and Ball 2006), and longer RDT, reflecting sustained attention (Friedman and Liebelt 1981; Pieters, Rosbergen, and Hartog 1996; Ryan and Cohen 2004) to failure-relevant events.

In addition, prior work indicates that rich communicative content is associated with deeper failure comprehension (Wu, 2020; Lin, Hou, and Chang 2022). Given that MFD has been established as an indicator of processing depth (Fitts, Jones, and Milton 1950; Just and Carpenter 1976; Velichkovsky, 2001; Pannasch 2003), we hypothesise that the mere opportunity to communicate similarly leads to increased MFD for failure-relevant events.

Based on these assumptions, we propose:

H1: Communication eye movement metrics for failure-relevant events. Specifically, compared to a baseline of no communication, this effect manifests as:

- **H1a:** shorter TTFF,
- **H1b:** a higher RFC,
- **H1c:** longer RDT, and
- **H1d:** longer MFD.

However, research on monitoring phases (Hasse and Bruder 2015; Bruder and Hasse 2020) suggests that the effect of communication availability on eye-movement metrics varies across the timeline of a failure event, leading to the following interaction hypothesis:

H2: The effect of communication availability on the visual processing of failure-relevant events varies

across monitoring phases, being most pronounced during the anticipation phase, followed by the detection phase. Specifically, compared to the other phases, this effect manifests as:

- **H2a:** shorter TTFF,
- **H2b:** a higher RFC,
- **H2c:** longer RDT, and
- **H2d:** longer MFD.

The novelty of this study lies in providing the first fine-grained quantification of individual eye-movement patterns during collaborative monitoring, comparing conditions with and without communication availability. By focusing on eye-movement metrics (TTFF, RFC, RDT, MFD), we offer objective evidence of how the mere structural opportunity to communicate—regardless of its content—influences individual eye-movement patterns, with potential implications for adaptive safety in socio-technical systems.

Method

A monitoring task was designed to examine how the opportunity to communicate influences monitoring behaviour in a group eye-tracking context. We selected teams of three to work together in the monitoring task, as this represents a small group, which is a suitable size for investigating team processes (Hackman 2002). Moreover, Steiner (1972) found that groups of three to five people tend to achieve better results than groups of two people due to better distributions of tasks and communication among members. Thus, we chose teams of three to balance the opportunity to study team processes with analytical tractability. The monitoring task was part of a Control Centre Task (ConCent) simulation (Schulze Kissing, 2016), which was combined with three eye trackers. To determine whether and, if so, which attentional processes are affected by communication, diverse eye-tracking parameters were used to measure specific attentional processes. To identify which specific monitoring phase in the overall monitoring process was most affected by communication, eye movements were categorised into monitoring phases. Figure 1 illustrates the overall test scenario of the monitoring task with a total of 48 intervals, three of which are failure intervals (marked in red). In each interval, the participants should go through the four phases—identification, verification, anticipation and detection—whereby a failure can only be detected in the failure intervals.

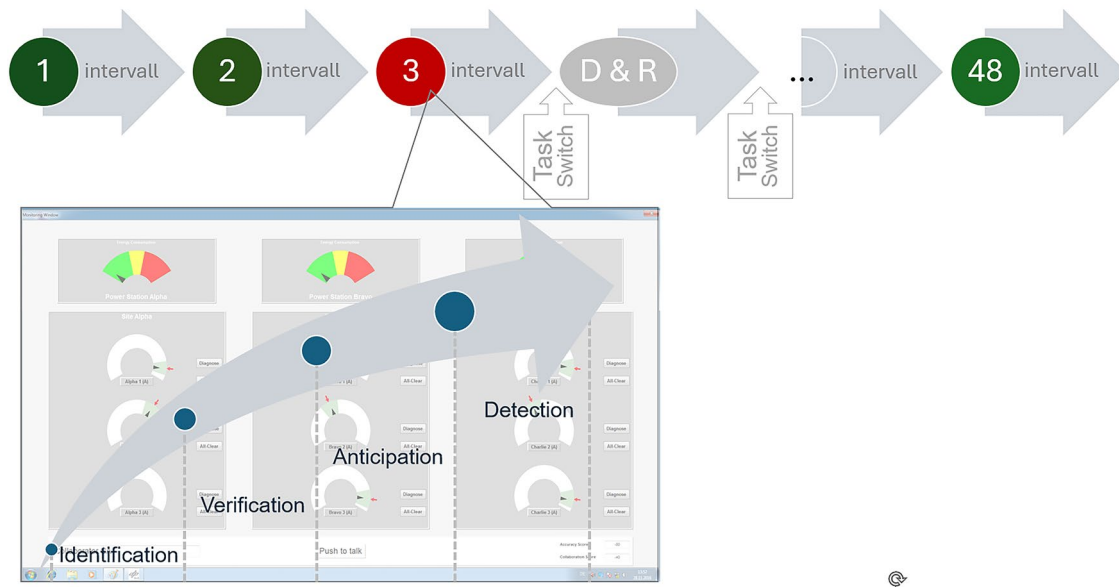


Figure 1. Illustration of the test scenario including the intervals and monitoring phases.

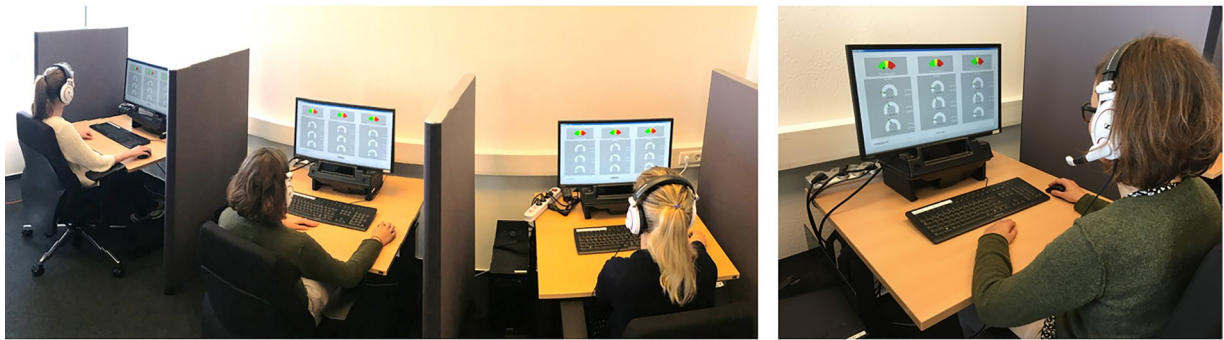


Figure 2. Integrated testing environment.

Simulation tool ConCent

ConCent was developed and validated to investigate psychosocial requirements for control room operators under controlled conditions (for further information: Bruder, Schadow, and Schulze Kissing 2019; Schulze Kissing, 2016). This includes monitoring for deviant system behaviour (monitoring task), identifying the cause of system deviations (diagnosis task), and deciding on how to fix the problem (remedy task). Although the three tasks—monitoring, diagnosis, and remedy—built upon each other, their construction and design within ConCent allow them to be treated independently. Since this paper presents findings that are concerned with the monitoring task, this task is described in more detail.

Monitoring task

Each team of three worked simultaneously, with individuals were separated by room dividers into partitioned

areas, each equipped with a computer and eye-tracking system. Figure 2 shows the integrated testing environment consisting of one test leader station (left) and three workstations.

At each workstation, operators had to monitor nine gauges, each displaying production output of one production facility. Three power station gauges displayed the energy status of one production site (see Figure 3).

Although the view of the power station gauges was shared by all three operators, each operator had a specific view on their own nine production facilities. To the right of each gauge of a production facility, two related response buttons labelled 'Diagnose' and 'All Clear' were displayed.

Regardless of communication availability, participants were required to monitor the gauges and corresponding power stations to detect system failures.

Therefore, participants had to learn how the automated system worked under normal conditions by continuously comparing the behaviour of the



Figure 3. Monitoring screen of ConCentT containing the displays of nine production facilities and three power stations, which are distributed over three locations.

energy displays with that of the individual production line gauges.

The normal status occurred when the production behaviour of individual gauges was reflected in the energy display level. The inherent logic of the monitoring task was that the energy level of the energy displays could only be high if more than one production gauge, which together with the corresponding energy display belongs to a production line, increased production. In other words, if only one production facility within a production line increased production, the energy indicator could not be high; if it was high, this indicated an abnormal process (i.e., a failure).

Participants learned that a failure was always preceded by a critical situation, which occurred when two conditions were met:

1. At just one gauge across in an entire production line, the tolerance range and then the current value changed.
2. The associated energy level turned red, indicating abnormally high energy.

When both conditions were met, the gauge became critical and required closer monitoring. If the critical gauge's value subsequently exceeded the tolerance range, this indicated a failure. At this point, the critical gauge was visible to everyone on the corresponding display, enabling failure detection even without communication. In other words, while all participants

usually only saw their own production site displays, they all saw the same display in the event of a critical gauge. Then, if the participants detected a failure, they were expected to press the 'Diagnose' button as quickly as possible. If the critical gauge's value returned to the tolerance range, it indicated no failure, and participants were expected to press the 'All Clear' button.

Each participant completed two test scenarios, each of which consisted of 48 30-second intervals. Of these, 24 were critical intervals, with failures occurring in three of them.

At the beginning of each interval, participants had to (a) check whether the first precondition for a critical gauge was met; (b) check whether the second precondition for a critical gauge was met; (c) closely monitor the critical gauge if it turned into a failure; (d) detect and report failure or give the all-clear within four seconds. Prior pilot testing confirmed that four seconds are sufficient to make a decision within the scope of the experimental task.

Experimental design

To investigate the impact of communication availability on monitoring relevant events, the monitoring task was designed so that it could be performed with or without communication (Figure 4). The independent variable was operationalised by manipulating radio communication across two conditions. In the 'communication off' condition, the radio was deactivated, and participants

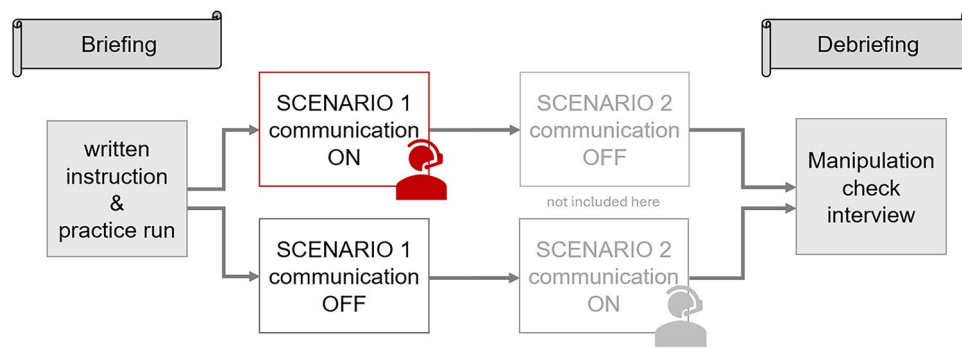


Figure 4. Illustration of the experimental design and the procedure.

were told the device had failed and that they had to monitor independently without team contact. In the ‘communication on’ condition, radio communication was available. However, participants were instructed to restrict their communication to task-relevant information, specifically the fulfilment of preconditions for critical events, critical gauges, and the occurrence of failures. In both conditions, the participants were required to monitor critical gauges to detect and report failures. Experience with computer games and with computers in general was surveyed as potential covariates. In addition, situational factors, such as noise and room lighting, were controlled or held constant. Two scenarios were developed to allow variation in both the monitoring and remedy tasks. Of these, only Scenario 1, which compared ‘communication on’ and ‘communication off’ groups, is relevant to our research questions.

The dependent variables assessed cognitive and behavioural dimensions of monitoring (e.g., perceptual speed, attentional focus, and processing depth), which were operationalised via diverse eye-tracking parameters. Additionally, failure detection performance was assessed as a complementary outcome (see Measurements for a detailed description of all metrics).

Eye-Tracking equipment

Eye movements were recorded remotely by using the Eye Follower System (LC Technologies, Inc.). The system operated at 120Hz and was combined with the simulation tool ConCenT to ensure that both systems used the same timestamp. The fixation-detection algorithm was set with a minimum sample for fixation detection of six gazes on a particular screen point—within the deviation threshold of 25 pixels.

Participants

The sample consisted of 144 participants, that is, 48 teams of three participants. Of this total, 15 teams

consisted of applicants for air traffic control training (ATC) at DFS (Deutsche Flugsicherung: German Air Traffic Control), while the remaining 33 teams involved students from different universities. All participants were between the ages of 18 and 49 ($M=23.01$, $SD=5.03$), 51% were female. To ensure sample homogeneity, we tested for performance differences by gender and participant type (students vs. aviation applicants). Single-factorial ANOVAs revealed no significant differences across all three performance parameters for either gender or participant type (all $F \leq 1.01$, all $p > .05$). All participants had either corrected or normal vision. ATC participants were recruited personally at DLR (German Aerospace Centre), Hamburg, and compensated with €25. Students were recruited via social media and with flyers posted on the campus of the University of Hamburg. In addition to the €25 participation payment, students received an extra €10 as reimbursement for their time and travel to the test site. This study was conducted in accordance with the model code of ethics of the European Federation of Psychologists’ Associations (<https://www.efpa.eu/model-code-ethics>) and the Declaration of Helsinki (ethics committee: DLR e. V., Geschäftsstelle Forschungsethik, 51170 Köln, Germany, approval number: 13/25). Participants were informed that their data will be evaluated anonymously, and they confirmed their voluntary participation in a study participant contract. All participants provided written informed consent prior to their participation.

Procedure

After filling out a demographic questionnaire, participants were instructed to assume the role of control room operators, receiving information about system monitoring, failure diagnosis, and problem-solving tasks (Figure 4). After a 10-minute practice scenario where they familiarised themselves with how to anticipate, detect, and report deviations from standard processes, the participants were calibrated to the eye-tracking system.

They then completed the first 45-minute test scenario, followed by a short break, recalibration, and the second 45-minute test scenario. Finally, a post-experiment (debriefing) interview with manipulation check was conducted to assess participants' perceptions of the study procedures. At the end, the participants were compensated. The total duration of the experiment was 2.5 hours.

Measurements

With regard to failure-detection performance, the number of correctly detected failures, response time, and the number of false alarms (incorrectly reported failures) were measured.

Eye movements were recorded while monitoring the distributed production processes as well as reporting system deviations. Eye-tracking data were automatically categorised into monitoring phases and related to relevant AOs through the event parser in the NYAN Software. The event parser synchronised eye movements with logged simulation events, enabling gaze data extraction based on start/end times or event names. For each monitoring phase time frame, relevant AOs were defined.

Defining AOs

The definition of AOs was directly connected to the operations of the automatic system, which could

potentially encounter a failure. Fixating on these AOs at the appropriate time should indicate ideal monitoring behaviour and enable operators to identify critical situations, anticipate, and detect failures. Figure 5 illustrates the AOs in the anticipation phase, exemplified for an interval with a failure at the production line in the middle.

Eye-Tracking parameters

To assess attentional focus—specifically whether communication influences the frequency and duration of gaze on relevant task elements—we employed relative rather than absolute eye movement measures. This approach follows the argument that relative parameters are more informative for capturing gaze behaviour (Rötting 2001; Hasse and Bruder 2015). RFC was calculated as the ratio between the number of fixations on relevant AOs and the total number of fixations within a given time frame. RDT was calculated as the ratio between the time spent on relevant AOs and the total time spent on all AOs. Both metrics result in a ratio ranging from 0 to 1, where higher values indicate a stronger attentional focus on task-relevant information.

To investigate whether the opportunity to communicate leads to a more intensive analysis of task-relevant information, we employed the MFD, calculated as the average duration (in ms) of all fixations on relevant AOs.

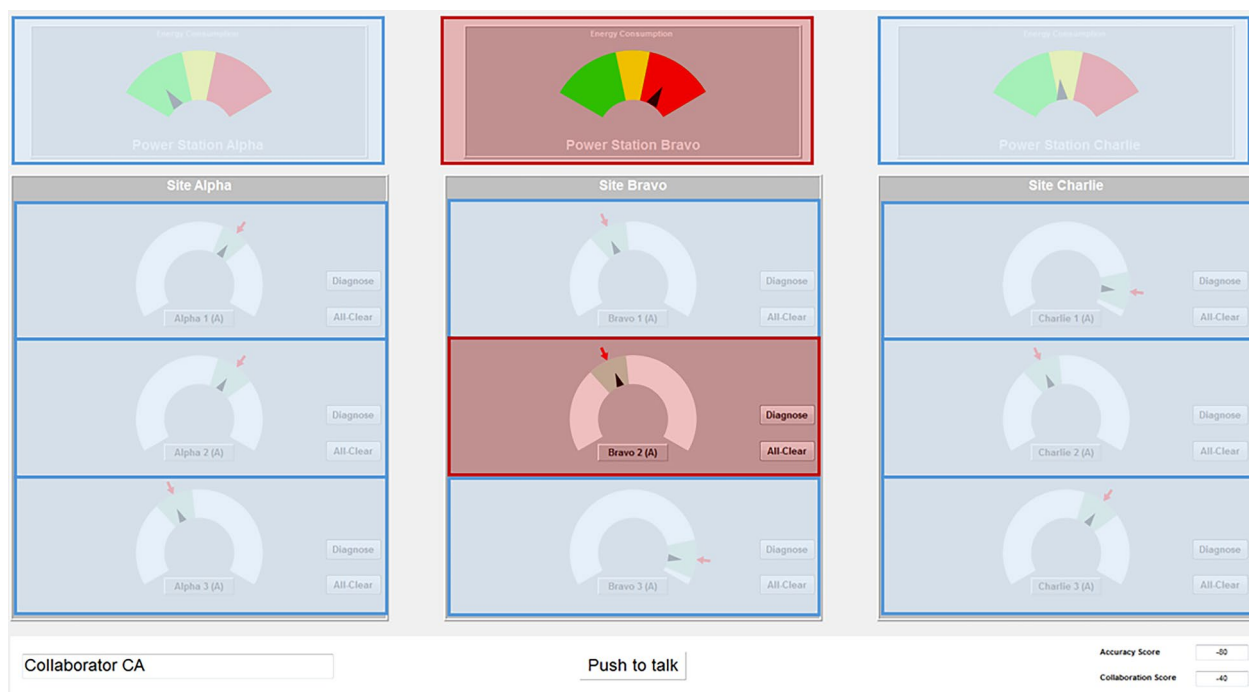


Figure 5. Illustration of the AOs on the monitoring screen. Two relevant AOs are highlighted in red, with all other AOs shown in blue.

To investigate whether communication enables team partners to locate relevant information more efficiently, we analysed the TTTF, measured as the time (in ms) elapsed until a participant first fixates on a relevant AOI.

Monitoring phases

The definition of time frames (times of interest) for eye-tracking data organisation was based on the monitoring phases of the normative model of monitoring behaviour (Bruder et al., 2014). Specifically, these phases corresponded to the task steps within a monitoring interval: (1) identification, (2) verification, (3) anticipation, and (4) detection (see also section *Monitoring Task*).

Unlike previous studies using alternative simulation tools (Hasse and Bruder 2015), ConCenT does not remain static at the beginning of each monitoring interval. Thus, instead of a “classic” orientation phase, ConCenT includes two orientation steps: the identification and the verification phase. During the identification phase, participants had to check whether the tolerance range and current value changed for just one gauge in a production line, which represents the first precondition for a gauge to become critical. During the subsequent verification phase, participants confirmed whether the previously identified gauge was actually critical. They checked whether the associated energy level turned red, indicating abnormally high energy. Only if this condition was met was the gauge classified as critical, requiring closer monitoring in the subsequent phases.

Following previous work (Hasse and Bruder 2015; Bruder and Hasse 2020), the anticipation phase was defined as the time before a possible failure, and the detection phase as the window in which a failure could occur. Conversely, the recheck phase was omitted from the task design, as previous research indicated it is not empirically reflected in eye-tracking data (e.g., Bruder and Hasse 2020).

Data selection and cleaning

Of the 144 participants, 140 passed the calibration process successfully; thus, only four eye-tracking datasets were excluded due to participant-specific tracking difficulties. Nine participants experienced short-term tracking disturbances during data recording which led to inaccuracies in the data identified via outlier analysis (standard deviation). These nine participants were excluded from the subsequent analyses, resulting in a final eye-tracking sample of $N=131$ (69 in the ‘communication on’ condition, 62 in the ‘communication off’ condition). For performance measures, no data were

lost, so all 144 participants are included in the following analyses.

To evaluate the effect of communication availability on monitoring behaviour, a three-factor mixed MANOVA was initially planned, including communication availability (between-subjects), monitoring phase (within-subjects), and interval (within-subjects, 6 levels: 3 failure intervals corresponding to the three failures in the scenario and 3 a priori selected, structurally identical critical intervals as high-risk non-failure contexts to ensure comparability). However, preliminary assumption checks revealed a severe homoscedasticity violation; due to insufficient cell sample sizes relative to the model’s complexity ($N=52$), Box’s M Test could not be computed. Diagnostic checks confirmed that this instability was driven by extreme variance heterogeneity in the third critical interval. To establish a mathematically valid and robust statistical framework, the model was simplified to a two-factor MANOVA (communication availability $\times$ phase) by removing the factor Interval. The problematic third critical interval was excluded, and data were aggregated across the remaining five intervals. This adjustment successfully resolved all multivariate assumption violations and allowed the analysis to be run for the full available sample of $N=131$ participants, maximising statistical power.

To ensure robustness, we compared the results of the simplified two-factor MANOVA with those from the original three-factor model (where computable, $N=52$). Despite the reduced power in the three-factor model, the pattern of significant effects for communication and phase remained consistent, with effect sizes in the same direction. This confirms that our substantive conclusions are robust to the specific interval selection and aggregation strategy.

Data analysis

For performance measures, team-level nesting was explicitly modelled as the primary analytical framework. Intraclass Correlation Coefficients (ICCs) were calculated for the three performance measures. Subsequently, univariate Mixed-Effects Models (LMMs) were fitted using Restricted Maximum Likelihood (REML) estimation with the experimental manipulation (communication on vs. off) as a fixed factor and team identity (*Team_ID*) as a random intercept. This multi-level approach ensures correct standard errors and accounts for potential variance inflation due to nested data structures.

For the main analysis of monitoring behaviour, the dependent variables (RFC, RDT, MFD, and TTTF on

relevant AOIs) were evaluated using the 2×4 mixed-design repeated measures MANOVA established above.

To address the nested data structure (48 teams), Intraclass Correlation Coefficients (ICCs) were also calculated for all eye-tracking metrics. While ICCs were negligible ($< .10$) for identification, verification, and detection phases, they reached up to 0.36 during the anticipation phases. To ensure these potential within-team dependencies did not compromise the validity of our results, we conducted sensitivity analyses using Linear Mixed-Effects Models (LMMs) with teams as random intercepts for all variables with ICCs $> .15$. These analyses consistently replicated the MANOVA patterns. Consequently, the MANOVA was favoured as the primary framework because it accounts for the multivariate structure of the highly inter-correlated metrics, controls the experiment-wide error rate, and facilitates a holistic, interpretable analysis of monitoring behaviour.

Results

The results are presented in two sections. First, the findings concerning participants' performance data are detailed, which were analysed using LMMs. This is followed by the results of the 2×4 mixed-design MANOVA conducted on the eye-tracking data, examining the main effects of communication availability and phase, as well as their interaction.

Performance data

The baseline model for detection rate indicated substantial team-level clustering ($ICC=.534$), confirming that 53.4% of the variance resided at the team level, thus validating the necessity of a multilevel approach. Controlling for team identity, the primary LMM revealed a statistically significant main effect of the experimental manipulation, $F(1, 46) = 28.965$, $p=.000$, $\eta^2 = .39$. The detection rate was substantially higher when communication was on ($M=59.78$, $SD=32.77$) compared to off ($M=27.29$, $SD=19.28$).

For false alarms, the baseline model yielded a negligible team-level dependence ($ICC=.030$). The primary LMM revealed no statistically significant main effect of

the experimental manipulation, $F(1, 46) = .224$, $p=.638$. Communication availability had no significant effect on the number of false alarms. For response time, the baseline model indicated an $ICC=0$, demonstrating complete statistical independence at the team level. The primary LMM revealed no statistically significant main effect of the experimental manipulation, $F(1, 46) = .062$, $p=.804$. Communication availability had no significant effect on the number of response time. Table 1 gives an overview on the descriptive statistics of performance measures.

Effect of communication availability on eye-tracking data

Assumptions for the repeated measures MANOVA were assessed. Box's M test indicated a violation of the homogeneity of covariance matrices (Box's $M=292.52$, $F(136, 50195) = 1.870$, $p < .001$), and Mauchly's test confirmed the violation of sphericity for all included parameters ($p < .05$). Minor violations of Levene's test for the between-subjects factor were also noted for six dependent variables. Despite these violations, the MANOVA approach was maintained due to the nearly balanced group sizes (69 vs. 62), which ensures the robustness of multivariate tests. Consequently, Pillai's Trace was chosen as the primary multivariate statistic—recognized for its robustness against covariance violations—and the degrees of freedom for all within-subjects univariate F -Tests were corrected using the Greenhouse-Geisser estimates.

Multivariate tests indicated a significant effect for communication availability ($F(4,126) = 14.28$, $p < .001$; $V=.31$, partial $\eta^2 = .31$) and phase ($F(12,118) = 29.41$, $p < .001$; $V=.75$, partial $\eta^2 = .75$), as well as an interaction between communication availability and phase ($F(12,118) = 11.47$, $p < .001$; $V=.54$, partial $\eta^2 = .54$) on the eye-tracking parameters.

Univariate tests revealed that communication availability had a significant effect within the relevant AOIs on RFC ($F(1,129) = 53.98$; $p < .001$; partial $\eta^2 = .30$), RDT ($F(1,129) = 42.46$; $p < .001$; partial $\eta^2 = .25$), and TTTF ($F(1,129) = 8.36$; $p < .01$; partial $\eta^2 = .06$). Participants' RFC and RDT on relevant AOIs were significantly higher when the participants could communicate than when

Table 1. Descriptive statistics for the performance parameters of the experimental conditions "Communication On" and "Communication Off".

Communication	N	Detection rate (in %)		Response time (in ms)		False alarms (in %)	
		M	SD	M	SD	M	SD
ON	75	59.78	32.77	2240	731	5.33	11.02
OFF	69	27.29	19.28	2209	678	6.76	17.92
All	144	44.21	31.62	2225	704	6.02	14.70

they could not. In addition, participants' TTTF were significantly shorter with communication than without.

The phase factor had a significant univariate effect on all the eye-tracking parameters on relevant AOs: RFC ($F(2,286) = 47.19$; $p < .001$; partial $\eta^2 = .27$), RDT ($F(2,283) = 40.73$; $p < .001$; partial $\eta^2 = .24$), MFD ($F(3,363) = 11.10$; $p < .001$; partial $\eta^2 = .08$) and TTTF ($F(3,339) = 28.31$; $p < .001$; partial $\eta^2 = .18$). Descriptively, RFC and RDT peaked during the anticipation phase, whereas MFD was highest during the detection phase. TTTF was shortest during the identification phase. Across parameters, the verification phase consistently elicited the lowest values or longest latencies, with post-hoc comparisons revealing significant differences between most phases (see Tables 2 and 3 for detailed values).

The interaction between the factors communication and phase had univariate effects on RFC [$F(2,286) = 37.69$; $p < .001$; partial $\eta^2 = .23$], RDT [$F(2,282) = 24.30$; $p < .001$; partial $\eta^2 = .16$], MFD [$F(3,363) = 5.07$; $p < .005$; partial $\eta^2 = .04$], and TTTF [$F(3,339) = 4.80$; $p < .005$; partial $\eta^2 = .04$]. Pairwise comparisons for RFC and RDT showed significant differences between the 'communication on' and 'communication off' condition in the verification, the anticipation and detection phases (all $p < .001$) with higher values in the 'communication on' condition. As shown in Tables 2 and 3, as well as in the interaction plots in Figure 6, this difference was most pronounced during the anticipation phase.

For MFD, pairwise comparisons revealed no significant differences between the communication conditions across any of the phases (all $p > .05$). For TTTF, a significant difference emerged exclusively during the detection phase ($p < .001$), with faster first fixations in the 'communication on' condition (see Figure 6).

Discussion

This study analysed how the mere opportunity to communicate affects eye-movement patterns during collaborative monitoring, thereby addressing a fundamental ergonomic design decision: whether a communication channel should be enabled or restricted at all (Bednar and Welch 2020; Pöhler et al. 2025; Kusk, Nouwens, and Lee 2026). While prior work establishes that goal-directed communication enhances performance (e.g. Gorman, Cooke, and Winner 2006; Kim et al. 2024), we extended this scope by isolating the effect of communication availability and pairing it with objective eye-movement data.

The finding that 60% of failures were detected in the 'communication on' condition, compared to only 27% in the 'communication off' condition, aligns with existing research showing that communication reduces

Table 2. Table of means: relative fixation counts and relative dwell times by monitoring phase and communication availability.

	Relative fixation counts (Proportion)		Relative dwell times (Proportion)	
	on	off	on	off
Identification	.40 (.13)	.38 (.12)	.39 (.12)	.38 (.11)
Verification	.39 (.16)	.24 (.07)	.40 (.15)	.27 (.10)
Anticipation	.59 (.23)	.32 (.08)	.58 (.22)	.35 (.13)
Detection	.48 (.15)	.33 (.10)	.49 (.15)	.36 (.10)

Note. SD in parentheses. Overall $N=131$, Communication On Condition $N=69$, Communication Off Condition $N=62$.

Table 3. Table of means: mean fixation durations and total times to first fixation by monitoring phase and communication availability.

	Mean fixation duration (ms)		Total time to first fixation (ms)	
	on	off	on	Off
Identification	193.48 (73.84)	209.23 (75.33)	1.09 (.35)	1.05 (.27)
Verification	213.40 (77.84)	214.04 (62.28)	1.72 (1.12)	1.93 (.92)
Anticipation	227.49 (79.34)	211.02 (66.05)	1.41 (.87)	1.56 (.95)
Detection	231.63 (73.54)	220.83 (68.25)	1.47 (.73)	2.11 (.83)

Note. SD in parentheses. Overall $N=131$, Communication On Condition $N=69$, Communication Off Condition $N=62$.

failure susceptibility (Harrison et al. 2024; Dong and Li 2025). Crucially, while prior studies attribute this benefit to the qualitative content of team speech, our results demonstrate that the mere structural opportunity to communicate increases detection rates, even when explicitly accounting for team-level clustering in our mixed-effects framework. Notably, this performance benefit was highly selective: communication availability increased detection success without altering response times or false alarm rates, indicating that higher detection rates were not simply bought at the expense of speed or accuracy trade-offs. Moving beyond these pure performance outcomes, our eye-tracking data allow us to reveal the associated attentional patterns that may explain this effect.

General effects of communication availability and monitoring phases

Irrespective of the specific eye-tracking parameter, the mere availability of a communication channel had a systematic effect on eye-movement metrics. This factor alone explained one third of the variance in the eye-tracking parameters, demonstrating a substantial effect on metrics that serve as indicators of attentional processes (Findlay and Gilchrist 2003). Additionally, the monitoring phase alone accounted for three quarters of the variance in the eye movements, suggesting that

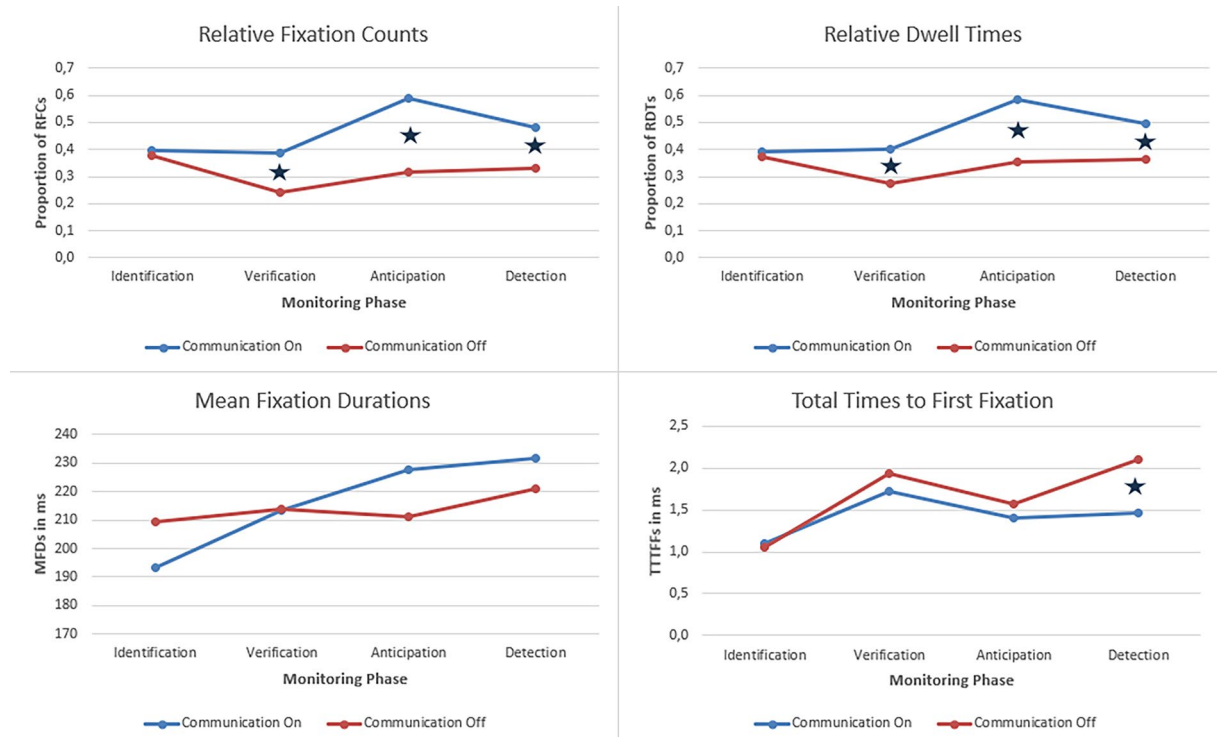


Figure 6. Interaction effects of communication (2 levels: communication, no communication) and monitoring phase (4 levels: identification, verification, anticipation, detection) on eye tracking parameters (estimated marginal means), such as relative fixation counts relative dwell times, mean fixation durations, and total times to first fixation.

a phase-specific approach may be appropriate when explaining the variance in eye movements during monitoring. Ultimately, the interaction effect between communication and phase accounted for half the variance in the eye-tracking parameters (54%). This interaction demonstrated its substantial relevance, and highlights that a differentiated, phase-by-phase analysis is essential for understanding how these eye-movement patterns are affected.

Main effect of communication availability

Overall, communication availability systematically had a systematic effect on eye-movement metrics, fully supporting hypotheses H1a, H1b, and H1c. Participants exhibited significantly higher RFC and RDT, alongside shorter TTFF on relevant AOIs when communication was available.

These findings align with prior research: While rich communicative content enhances failure detection (Harrison et al. 2024; Dong and Li 2025) and guides visual search towards critical cues (Kontogiannis and Malakis 2009; Niehorster et al. 2019), our results show that the mere opportunity to communicate yields similar effects on eye-movement patterns. Specifically, shorter TTFF values, linked to perceptual speed in prior work (Byrne et al. 1999; Rötting 2001; Joos,

Rötting, and Velichkovsky 2003), reflect faster visual attention allocation to failure-relevant events. Similarly, higher RFC and longer RDT values, indicators of attentional focus and sustained attention (Friedman and Liebelt 1981; Pieters, Rosbergen, and Hartog 1996; Jacob and Karn 2003; Ryan and Cohen 2004; Poole and Ball 2006), demonstrate enhanced prioritisation and maintenance of focus on critical information. Thus, our findings extend prior work showing that verbal exchange improves performance through prioritising task-relevant information (Poole and Ball 2006; Knott et al. 2007; Tollner-Burngasser et al., 2010). Crucially, our results reveal that these effects occur regardless of teamwork quality, suggesting that the mere opportunity for communication is sufficient to influence eye-movement patterns in ways that may contribute to operators' orientation towards critical events.

Conversely, H1d was not supported; MFD did not differ between conditions, indicating that communication availability did not affect MFD, a measure linked to processing depth in prior work (Velichkovsky, 2001; Panasch 2003).

Phase-dependent communication effects

Regarding the phase-specific effects, hypotheses H2a, H2b and H2c were fully supported. For RFC and RDT

(H2b, H2c), the effects of communication availability spanned across multiple phases—being most pronounced during the anticipation phase, remaining highly significant during the detection and verification phases, and vanishing only in the identification phase. Crucially, H2a was supported as a localised effect: a significant acceleration in TTFF emerged exclusively during the detection phase. Conversely, H2d was not supported, as MFD did not differ significantly between conditions in any phase.

The prominence of the anticipation phase for RFC and RDT aligns with earlier findings (Hasse and Bruder 2015; Barzantny 2024) and research on look-ahead fixations for advanced planning (Lehtonen et al. 2013; Pelz & Canosa, 2001). In this pre-event window, participants showed anticipatory fixation patterns, consistent with Wickens et al. (2001), who posited that monitoring is driven by the expectation of critical traffic events.

Once the failure manifested in the detection phase, RFC and RDT were joined by a significantly faster failure recognition (TTFF). This pattern of eye-movement metrics aligns with teamwork literature showing that oral communication speeds up team processes and enhances failure detection (Salas et al. 1995; Gorman, Cooke, and Winner 2006; Carvalho, Vidal, and Carvalho 2007; Bruder, Schadow, and Schulze Kissing 2019).

However, the lack of differences in MFD across all phases underscores that while communication availability affects eye-movement metrics such as RFC, RDT, and TTFF, it did not affect MFD, a measure linked to processing depth in prior work (Velichkovsky, 2001; Pannasch 2003).

Conclusion

In summary, this study demonstrates that communication availability influences eye-movement patterns during collaborative monitoring of automated systems. Our findings show that the mere opportunity to communicate increases RFC and RDT on failure-relevant events across all phases, particularly in the anticipation phase, and reduces TTFF in the detection phase. By identifying these patterns, we demonstrate how communication availability modulates visual attention. Ultimately, these effects may contribute to improved monitoring and anticipation of failures in team settings.

Practical implications

These findings offer valuable implications for workplace design, personnel selection, and operator training in highly automated environments. From an ergonomic perspective, introducing a communication

channel is not a neutral system parameter; depending on task demands, it carries inherent trade-offs between collaborative support and potential distraction (Idaszak 1989; Brummelhuis, Hoeven, and Toniolo-Barrios 2021; Murthy et al., 2025). Effective ergonomic design should consider communication channels not just as optional features, but as essential elements that influence individual eye-movement patterns. As these eye-movement patterns have been shown to be associated with focused, sustained, and rapid attention allocation to failure-relevant events (Friedman and Liebelt 1981; Byrne et al. 1999; Jacob and Karn 2003; Pannasch 2003), communication channels may thus contribute to improvements in human monitoring performance and, consequently, overall system safety.

Personnel selection and training may benefit from targeting both individual and team monitoring capabilities. The ConCenT monitoring task combined with eye tracking offers a promising tool for evaluating team monitoring behaviour, which may serve as a foundation for developing future selection and training programs.

Results suggest that a special focus should be placed on the anticipation phase when selecting or training future personnel working in control rooms, specifically regarding attention allocation across relevant AOs (in terms of RFC, RDT, and TTFF). While bounded by the specific task structure of our simulation, these ergonomic insights offer tentative design considerations for other team-based domains—such as distributed command and control centres or collaborative robotics—where rapid attention allocation and reduced attentional gaps are critical.

Limitations and future research

In our study, we opted for groups of three as this provides a good balance between the opportunity to study the team processes and the need to analyse the results. Further research is needed to confirm that our results are also relevant for groups of other sizes.

The focus of the present study was on the effects of communication availability on eye-movement metrics, where the opportunity for verbal exchange was treated as an independent factor. Whether these eye-movement patterns reflect deeper cognitive calibration, the formation of SMM (e.g., Andrews et al. 2023; Carraro, Furlan, and Netland 2025; Esmaeili et al. 2025), or workload reduction (e.g., Hasse, Grasshoff, and Bruder 2014; Li-Wang et al., 2023; Möhlenbrink, 2011) remains an open question for future process-based analyses (e.g., through transcript coding). In this regard, eye tracking measures could be

combined with psychophysiological or subjective workload scales to investigate how qualitative communication patterns shape cognitive work regulation.

A methodological consideration concerns the team-level variability and potential statistical dependencies. Because teams were free to interact when communication was enabled, the specific quality, timing, and style of verbal interaction naturally varied from team to team. This unmeasured qualitative variation introduced statistical clustering at the team level for the failure detection rate and anticipatory gaze behaviour. To account for these team-level dependencies, we employed LMMs, confirming that our primary findings remain robust. Nevertheless, because qualitative verbal protocols were not recorded or coded, the exact interaction dynamics driving this team-level variance remain an open question. Future research should combine eye-tracking with content analysis to explore how specific interaction styles modulate these structural effects.

Standard eye-tracking metrics, including RFC, RDT, TTTF, and MFD in relation to predefined AOIs, characterise individual visual attention (e.g. Friedman and Liebelt 1981; Byrne et al. 1999; Jacob and Karn 2003; Pannasch 2003). However, analysing these parameters at the team level—specifically examining inter-team variations, similarities, and dependencies—offers the potential for a comparative understanding of collaborative versus individual monitoring performance. This represents a promising future approach for analysing eye-tracking data collected in group eye-tracking contexts.

Acknowledgements

We thank our colleague **Dirk Schulze-Kissing** who developed the ConCent Simulation, and contributed significantly to the conception, design, and implementation of the study.

We would also like to thank our former trainee **Marc Latz** who contributed to the experimental procedure and the eye tracking data preparation.

Finally, we would like to express our gratitude to **Johannes Bernau**, **Jasmin Chadha**, **Julia Lange**, and **Katharina Utesch** for their valuable time and support in proofreading this manuscript.

Author contributions

CRedit: **Catrin Hasse**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; **Carmen Bruder**: Conceptualization, Investigation, Methodology, Project administration, Visualization, Writing – review & editing.

Disclosure statement

There are no relevant financial or non-financial competing interests to report.

Funding

No funding was received.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- Andrews, R. W., J. M. Lilly, D. Srivastava, and K. M. Feigh. 2023. "The Role of Shared Mental Models in human-AI Teams: A Theoretical Review." *Theoretical Issues in Ergonomics Science* 24 (2): 129–175. doi:10.1080/1463922X.2022.2061080.
- Barzantny, C. 2024. "Monitoring in Air Traffic Control: The Use of Eye Tracking in Future Training." [Dissertation, Technische Universität Dresden, Dresden]. Deutsche Nationalbibliothek.
- Bednar, P. M., and C. Welch. 2020. "Socio-Technical Perspectives on Smart Working: Creating Meaningful and Sustainable Systems." *Information Systems Frontiers* 22 (2): 281–298. doi:10.1007/s10796-019-09921-1.
- Bruder, C., and C. Hasse. 2019. "Differences between Experts and Novices in the Monitoring of Automated Systems." *International Journal of Industrial Ergonomics* 72: 1–11. doi:10.1016/j.ergon.2019.03.007.
- Bruder, C., and C. Hasse. 2020. "What the Eyes Reveal: Investigating the Detection of Automation Failures." *Applied Ergonomics* 82: 102967. doi:10.1016/j.apergo.2019.102967.
- Bruder, C., H. Eißfeldt, P. Maschke, and C. Hasse. 2014. "A Model for Future Aviation." *Aviation Psychology and Applied Human Factors* 4 (1): 13–22. doi:10.1027/2192-0923/a000051.
- Bruder, C., J. Schadow, and D. Schulze Kissing. 2019. "Oral Communication as a Performance Indicator in Control Rooms." In *Proceedings of the 33rd Conference of the European Association for Aviation Psychology* (133–147. European Association for Aviation Psychology.
- Bruder, C., L. Jörn, and H. Eißfeldt. 2008. "Aviator 2030 – When Pilots and Air Traffic Controllers Discuss Their Future." In A. Droog & T. D'Oliveira (Eds.), *Proceedings of the 28th Conference of the European Association for Aviation Psychology* (354–358). EAAP.
- Brummelhuis, L. L. ten., C. L. ter Hoeven, and M. Toniolo-Barrios. 2021. "Staying in the Loop: Is Constant Connectivity to Work Good or Bad for Work Performance?" *Journal of Vocational Behavior* 128: 103589. doi:10.1016/j.jvb.2021.103589.
- Byrne, M. D., J. R. Anderson, S. Douglass, and M. Matessa. 1999. "Eye Tracking the Visual Search of Click-down Menus." In M. G. Williams & M. W. Altom (Eds.), *Proceedings of the SIGCHI Conference on Human Factors in Computing*

- Systems the CHI is the limit - CHI '99 (402–409). ACM Press. doi:[10.1145/302979.303118](https://doi.org/10.1145/302979.303118).
- Carraro, M., A. Furlan, and T. Netland. 2025. "Unlocking Team Performance: How Shared Mental Models Drive Proactive Problem-Solving." *Human Relations* 78 (4): 407–437. doi:[10.1177/00187267241247962](https://doi.org/10.1177/00187267241247962).
- Carvalho, P. V., M. C. Vidal, and E. F. de Carvalho. 2007. "Nuclear Power Plant Communications in Normative and Actual Practice: A Field Study of Control Room Operators' Communications." *Human Factors and Ergonomics in Manufacturing & Service Industries* 17 (1): 43–78. doi:[10.1002/hfm.20062](https://doi.org/10.1002/hfm.20062).
- Dong, X., and Z. Li. 2025. "Exploring Connections Between Team Process and Automation Error Management." *International Journal of Human-Computer Interaction* 41 (11): 6637–6648. doi:[10.1080/10447318.2024.2382517](https://doi.org/10.1080/10447318.2024.2382517).
- Eaglestone, J., D. Damos, H.-J. Hörmann, K. Stadler, and J. Wium. 2022. *Selection in Aviation. A European Association for Aviation Psychology report*. European Association for Aviation Psychology.
- Eiðfeldt, H. 2017. "Operational Monitoring in Aviation: A Scale and Some Findings." In *Thinking, High and Low: Cognition and Decision Making in Aviation. Proceedings of the 32nd Conference of the European Association for Aviation Psychology* (386–396). European Association for Aviation Psychology.
- Eiðfeldt, H., and K. Gayraud. 2015. "Shifts in Ability Requirements as Perceived Among Aviation Operators." *Procedia Manufacturing* 3: 2543–2549. doi:[10.1016/j.promfg.2015.07.549](https://doi.org/10.1016/j.promfg.2015.07.549).
- Eiðfeldt, H., D. Grasshoff, C. Hasse, H.-J. Hörmann, D. Schulze-Kissing, C. Stern, J. Wenzel, and O. Zierke. 2009. "Aviator 2030 – Ability Requirements in Future ATM Systems II: Simulations and Experiment." (DLR Forschungsbericht 2009-28). DLR.
- Esmaili, R., M. Yazdi, M. Rismanchian, and M. Shakerian. 2025. "Unveiling the Dynamics of Team Cognition in Emergency Response Teams." *Frontiers in Psychology* 16: 1534224. doi:[10.3389/fpsyg.2025.1534224](https://doi.org/10.3389/fpsyg.2025.1534224).
- Findlay, J. M., and I. D. Gilchrist. 2003. *Active Vision*. Oxford, UK: Oxford University Press.
- Fitts, P. M., R. E. Jones, and J. L. Milton. 1950. "Eye Movements of Aircraft Pilots during Instrument-Landing Approaches." *Aeronautical Engineering Review* 9 (2): 24–29.
- Friedman, A., and L. S. Liebelt. 1981. "On the Time Course of Viewing Pictures with a View towards Remembering." In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), *Eye Movements: Cognition and Visual Perception* (137–155). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Gorman, J. C., N. J. Cooke, and J. L. Winner. 2006. "Measuring Team Situation Awareness in Decentralized Command and Control Environments." *Ergonomics* 49 (12-13): 1312–1325. doi:[10.1080/00140130600612788](https://doi.org/10.1080/00140130600612788).
- Hackman, J. R. 2002. *Leading Teams: Setting the Stage for Great Performances*. Boston, MA: Harvard Business School Press.
- Harrison, J. L., S. Zhou, M. J. Scalia, D. A. P. Grimm, M. Demir, N. J. McNeese, N. J. Cooke, and J. C. Gorman. 2024. "Communication Strategies in Human-Autonomy Teams During Technological Failures." *Human Factors* 66 (11): 2539–2555. doi:[10.1177/00187208231222119](https://doi.org/10.1177/00187208231222119).
- Hasse, C., and C. Bruder. 2015. "Eye-Tracking Measurements and Their Link to a Normative Model of Monitoring Behaviour." *Ergonomics* 58 (3): 355–367. doi:[10.1080/00140139.2014.967310](https://doi.org/10.1080/00140139.2014.967310).
- Hasse, C., C. Bruder, D. Grasshoff, and H. Eiðfeldt. 2009. "Future Ability Requirements for Human Operators in Aviation." In D. Harris (Ed.), *Lecture Notes in Computer Science. Engineering Psychology and Cognitive Ergonomics* (Vol. 5639, 537–546). Berlin, Germany: Springer. doi:[10.1007/978-3-642-02728-4_57](https://doi.org/10.1007/978-3-642-02728-4_57).
- Hasse, C., D. Grasshoff, and C. Bruder. 2012a. "How to Measure Monitoring Performance of Pilots and Air Traffic Controllers." In S. N. Spencer (Ed.), *Proceedings of the Symposium on Eye Tracking Research and Applications (ETRA '12)* (409–412). ACM.
- Hasse, C., D. Grasshoff, and C. Bruder. 2012b. "Eye-Tracking Parameters as a Predictor of Human Performance in the Detection of Automation Failures." In D. de Waard, K. Brookhuis, F. Dehais, C. Weikert, S. Röttger, D. Manzey, S. Biede, F. Reuzeau, & P. Terrier (Eds.), *Human Factors: A View from an Integrative Perspective* (133–144). Maastricht, The Netherlands: HFES Europe Chapter.
- Hasse, C., D. Grasshoff, and C. Bruder. 2014. "The Effect of Teamwork on Monitoring Performance and the Related Eye Movements. In." *Proceedings of the International Conference on Human-Computer Interaction in Aerospace* (pp. 1–8). ACM. doi:[10.1145/2669592.2669657](https://doi.org/10.1145/2669592.2669657).
- Hasse, C., H. Eiðfeldt, P. Maschke, and C. Bruder. 2013. "Using Eye Tracking to Describe Monitoring Behaviour during a Passive and an Active Control Task." *Journal of Eye Movement Research* 6 (3): 272.
- Hauland, G. 2008. "Measuring Individual and Team Situation Awareness During Planning Tasks in Training of En Route Air Traffic Control." *The International Journal of Aviation Psychology* 18 (3): 290–304. doi:[10.1080/10508410802168333](https://doi.org/10.1080/10508410802168333).
- Holmqvist, K., M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, and J. Van de Weijer. 2011. *Eye Tracking: A Comprehensive Guide to Methods and Measures*. Oxford, UK: Oxford University Press.
- Idaszak, J. R. 1989. "Human Operators in Automated Systems: The Impact of Active Participation and Communication." *Proceedings of the Human Factors Society Annual Meeting* 33 (13): 778–782. doi:[10.1177/154193128903301302](https://doi.org/10.1177/154193128903301302).
- Inhoff, A.W., and R. Radach. 1998. "Definition and Computation of Oculomotor Measures in the Study of Cognitive Processes." *Eye Guidance Inreading, Driving and Scene Perception* 29–53. Elsevier.
- Jacob, R. J. K., and K. S. Karn. 2003. "Commentary on Section 4. Eye Tracking in Human-Computer Interaction and Usability Research: Ready to Deliver the Promises." In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research* (573–605). Amsterdam, The Netherlands: Elsevier.
- Joos, M., M. Rötting, and B. M. Velichkovsky. 2003. "Bewegungen Des Menschlichen Auges: Fakten, Methoden, Innovative Anwendungen." In G. Rickheit, T. Herrmann, & H. Deutsch (Eds.), *Psycholinguistik/Psycholinguistics: Ein Internationales Handbuch/An International Handbook* (142–168). Berlin, Germany: De Gruyter.
- Just, M. A., and P. A. Carpenter. 1976. "Eye Fixations and Cognitive Processes." *Cognitive Psychology* 8 (4): 441–480. doi:[10.1016/0010-0285\(76\)90015-3](https://doi.org/10.1016/0010-0285(76)90015-3).

- Kim, J., S. Ishdorj, J. Jeon, and J. Kim. 2024. "Identifying Vital Factors for Enhancing Safety Communication among Foreign Construction Field Workers." *Buildings* 14 (6): Article 1714. doi:10.3390/buildings14061714.
- Knott, C. C., W. T. Nelson, M. K. McCroskey, and B. T. Miller. 2007. "Do You See What I See? Effects of Communication on Scanning Strategies in Change Detection by Individuals and Teams of Observers." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 51 (18): 1186–1190. doi:10.1177/154193120705101828.
- Kontogiannis, T., and S. Malakis. 2009. "A Proactive Approach to Human Error Detection and Identification in Aviation and Air Traffic Control." *Safety Science* 47 (5): 693–706. doi:10.1016/j.ssci.2008.09.007.
- Kusk, K., M. Nouwens, and M. K. Lee. 2026. "Moderating the Workplace: Governing Communication Channels for Platform Workers." In N. Oliver, D. A. Shamma, H. Candello, P. Cesar, P. Lopes, A. Bozzon, T. Kosch, V. Liao, X. Ma, V. Artizzu, F. Draxler, G. López, A. V. Reinschluessel, X. Tong, & P. O. Touns Dugas (Eds.), *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems* (1–12). ACM. doi:10.1145/3772318.3790554.
- Lehtonen, E., O. Lappi, H. Kotkanen, and H. Summala. 2013. "Look-Ahead Fixations in Curve Driving." *Ergonomics* 56 (1): 34–44. doi:10.1080/00140139.2012.739205.
- Li-Wang, J., A. Townsley, and R. Katta. 2023. "Cognitive Ergonomics: a Review of Interventions for Outpatient Practice." *Cureus* 15 (8): e44258. 10.7759/cureus.44258. 37772235
- Lin, P.-C., H.-T. Hou, and K.-E. Chang. 2022. "The Development of a Collaborative Problem Solving Environment That Integrates a Scaffolding Mind Tool and Simulation-Based Learning: An Analysis of Learners' Performance and Their Cognitive Process in Discussion." *Interactive Learning Environments* 30 (7): 1273–1290. doi:10.1080/10494820.2020.1719163.
- Möhlenbrink, C., A. Papenfuß, and J. Jakobi. 2011. "The Role of Workload for Work Organisation in a Remote Tower Control Center." In *ATM-Seminar 2011*. Berlin, Germany.
- Niehorster, D. C., T. Cornelissen, K. Holmqvist, and I. Hooge. 2019. "Searching with and against Each Other: Spatiotemporal Coordination of Visual Search Behavior in Collaborative and Competitive Settings." *Attention, Perception & Psychophysics* 81 (3): 666–683. doi:10.3758/s13414-018-01640-0.
- Niessen, C., and K. Eyferth. 2001. "A Model of the Air Traffic Controller's Picture." *Safety Science* 37 (2-3): 187–202. doi:10.1016/S0925-7535(00)00048-5.
- Pannasch, S. 2003. "Ereignisbezogene Veränderungen Der Visuellen Fixationsdauer." [Doctoral dissertation, Technische Universität Dresden]. Qucosa. <https://nbn-resolving.org/urn:nbn:de:swb:14-1066398523687-97846>.
- Papenfuss, A. 2013. "Phenotypes of Teamwork – an Exploratory Study of Tower Controller Teams." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 57 (1): 319–323. doi:10.1177/1541931213571070.
- Pelz, J. B., and R. Canosa. 2001. "Oculomotor Behavior and Perceptual Strategies in Complex Tasks." *Vision Research* 41 (25-26): 3587–3596. doi:10.1016/S0042-6989(01)00245-0. 11718797
- Pieters, R., E. Rosbergen, and M. Hartog. 1996. "Visual Attention to Advertising: The Impact of Motivation and Repetition." *Advances in Consumer Research* 23: 242–248.
- Pöhler, J., N. Flegel, T. Mentler, and K. van Laerhoven. 2025. "Keeping the Human in the Loop: are Autonomous Decisions Inevitable?" *i-com* 24 (1): 9–25. doi:10.1515/icom-2024-0068.
- Poole, A., and L. J. Ball. 2006. "Eye Tracking in HCI and Usability Research: Current Status and Future Prospects." In C. Ghaoui (Ed.), *Encyclopedia of Human Computer Interaction* (211–219). Hershey, PA: Idea Group.
- Rötting, M. 2001. *Parametersystematik Der Augen- Und Blickbewegungen Für Arbeitswissenschaftliche Untersuchungen*. Aachen, Germany: Shaker.
- Ryan, J., and N. Cohen. 2004. "The Nature of Change Detection and Online Representations of Scenes." *Journal of Experimental Psychology. Human Perception and Performance* 30 (5): 988–1015. doi:10.1037/0096-1523.30.5.988.
- Salas, E., C. Prince, D. P. Baker, and L. Shrestha. 1995. "Situation Awareness in Team Performance: Implications for Measurement and Training." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 37 (1): 123–136. doi:10.1518/001872095779049525.
- Salas, E., N. J. Cooke, and M. A. Rosen. 2008. "On Teams, Teamwork, and Team Performance: Discoveries and Developments." *Human Factors* 50 (3): 540–547. doi:10.1518/001872008X288457.
- Schulze Kissing, D. (2016). *Der Einsatz Synthetischer Aufgabenumgebungen zur Untersuchung kollaborativer Prozesse in Leitzentralen am Beispiel der "generic Control Centre Task Environment"* (ConCent). doi:10.17185/DUEPUBLICO/42384.
- SESAR JU 2020. *The European ATM Master Plan in a Nutshell*.
- Sharma, C., P. Bhavsar, B. Srinivasan, and R. Srinivasan. 2016. "Eye Gaze Movement Studies of Control Room Operators: A Novel Approach to Improve Process Safety." *Computers & Chemical Engineering* 85: 43–57. doi:10.1016/j.compchemeng.2015.09.012.
- Single European Sky ATM Research 3 Joint Undertaking 2024. *European ATM Master Plan: Making Europe the Most Efficient and Environmentally Friendly Sky to Fly in the World* (2025 edition). Luxembourg, Luxembourg: Publications Office of the European Union. doi:10.2829/9855255.
- Steiner, I. D. 1972. *Group Process and Productivity. Social Psychology*. New York, NY, USA: Academic Press.
- Svensson, Å., J. Lundberg, C. Forsell, and N. Rönnerberg. 2021. "Automation, Teamwork, and the Feared Loss of Safety." In P. Marti, O. Parlange, & A. Recupero (Eds.), *European Conference on Cognitive Ergonomics 2021* (1–8). ACM. doi:10.1145/3452853.3452855.
- Tollner-Burngasser, A., M. A. Riley, and W. T. Nelson. 2010. "Individual and Team Susceptibility to Change Blindness." *Aviation, Space, and Environmental Medicine* 81 (10): 935–943. doi:10.3357/ase.2809.2010.
- Velichkovsky, B. M. 2001. "Levels of Processing: Validating the Concept." In M. Naveh-Benjamin, M. Moscovitch, & H. L. Roediger (Eds.), *Perspectives on Human Memory and Cognitive Aging: Essays in Honour of Fergus I. M. Craik* (48–70). Philadelphia, PA, USA: Psychology Press.
- Venkatesha Murthy, S., Y. Lee, W. Doh, Y. Goh, and S.-H. Kim. 2025. "Examining Transparency Needs and Display Features: An Empirical Study of Dynamic Dual-Task HAT Simulation with AI Integration." *Proceedings of the Human*

- Factors and Ergonomics Society Annual Meeting* 69 (1): 313–319. doi:[10.1177/10711813251368830](https://doi.org/10.1177/10711813251368830).
- Vicente, K. J., E. M. Roth, and R. J. Mumaw. 2001. "How Do Operators Monitor a Complex, Dynamic Work Domain? The Impact of Control Room Technology." *International Journal of Human-Computer Studies* 54 (6): 831–856. doi:[10.1006/ijhc.2001.0463](https://doi.org/10.1006/ijhc.2001.0463).
- Wickens, C. D., J. Helleberg, J. Goh, X. Xu, and W. J. Horrey. 2001. Pilot Task Management: Testing an Attentional Expected Value Model of Visual Scanning (ARL-01-14/NASA-01-7). University of Illinois, Aviation Research Laboratory.
- Wium, J., and J. Eaglestone. 2022. "Job Analysis for Air Traffic Control." *Aviation Psychology and Applied Human Factors* 12 (1): 31–49. doi:[10.1027/2192-0923/a000218](https://doi.org/10.1027/2192-0923/a000218).
- Wu, S.-Y. 2020. "Incorporation of Collaborative Problem Solving and Cognitive Tools to Improve Higher Cognitive Processing in Online Discussion Environments." *Journal of Educational Computing Research* 58 (1): 249–272. doi:[10.1177/0735633119828044](https://doi.org/10.1177/0735633119828044).
- Yeong, S. S., and A. W. Shah Rollah. 2016. "The Mediating Effect of Safety Culture on Safety Communication and Human Factor Accident at the Workplace." *Asian Social Science* 12 (12): 127. doi:[10.5539/ass.v12n12p127](https://doi.org/10.5539/ass.v12n12p127).