# Operator Information Acquisition in Excavators – Insights from a Field Study Using Eye-Tracking

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**Abstract.** Poor operator direct sight can lead to collisions between excavators and humans, especially during reversing movements. Viewing aids, such as mirrors and camera monitor systems (CMS) are intended to compensate this. As empirical evidence on operators' visual information acquisition is scarce, this study investigated utilization of mirrors and CMS during regular work on construction sites by using eye-tracking and task observation. Results show that, during reversing movements, especially the left mirror and the CMS monitor were used. Implications of utilization and neglect are discussed with regard to safety and machinery design, such as configuration of viewing aids.

**Keywords:** Accident prevention · Earth-moving machinery · Viewing aids · Camera monitor systems · Closed-circuit television CCTV · Situation awareness

## 1 Introduction

Among earth-moving machinery, hydraulic excavators have accounted for the majority of registered accidents during the last years [1] and a considerable number of these were related to collisions between the machine and humans during reversing movements or rotating of the upper structure [2]. While tragic for all people involved, accidents cause delays in the work process, and can also imply investigations by law enforcement.

A plausible explanation for many collision accidents can be a lack of direct or indirect operator sight from the cabin to the surrounding area. The machine's counter-weight and the boom obstruct direct sight and thus make recognition of humans in the vicinity of the machine difficult for operators. Compensating this to some extent, operators can use different rearview mirrors, which are usually installed in varying number and configuration. Additionally, manufacturers and individual construction companies have begun to install camera monitor systems (CMS) displaying images of the rear area or the right side on a monitor in the cabin. Moreover, some parts around the machine, such as the left side, can be seen directly but require operators to turn their head. Thus, a number of different and partly redundant information sources exist, that can be useful to support operators' understanding of the surrounding for


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reversing and other movements. However, it remains largely unclear how excavator operators actually acquire visual information during regular work activity.

Therefore, the current study was initiated by the German Social Accident Insurance Institution for the Building Trade (BG BAU). As a first step, the aim was to find out whether and, if so, how operators use mirrors, CMS monitors and direct sight for reversing movements. In conjunction with subsequent studies, results can support future measures of prevention to further decrease accidents.

## 2 Related Work

### 2.1 Accident Prevention, Information Acquisition and Situation Awareness

Construction sites are highly dynamic workplaces where a variable number of workers and machines interact in a changing physical environment. Excavators add to the dynamic by their high movement variability, thus increasing the risk of collisions. Organizational measures of prevention have a long history on construction sites and relate to rules and procedures, such as traffic patterns, optimized material flow, restricted areas around the machine, stopping rules for the operator, or a banksman for maneuvering. Personal measures of prevention can include safety instructions, operator training, or protective equipment, such as warning wests or transponder systems (for German regulations see [3]). Although these are important additional measures to prevent collisions, priority has to be given to technical measures to enhance visibility, such as enlarged cabin windows, shorter machine tails, and additional viewing aids (i.e. mirrors or CMS).

With regard to the latter, excavators are usually equipped with a rearview mirror left of the cabin and one or more rearview mirrors right of the cabin, which display the lateral and rear areas of the machine. In some cases, right mirrors are arranged in such a way that, independent of the boom's position, at least one mirror can be seen from the cabin. Parabolic mirrors on the counterweight are used on older excavators to display the area immediately behind the machine, but require operators to turn their body and head. This can be avoided by using CMS that display the area directly behind the machine on a monitor in the cabin.

Working with excavators can place high demands on the operator in terms of visual information acquisition and processing. While performing their primary excavating tasks, operators need to be informed about the conditions of the machine (i.e. position, engine status) and that of loaded materials (i.e. stability), while being aware of the surrounding environment (i.e. humans or obstacles). Situation Awareness relates to this latter aspect, and states that the system shall inform the operator about the elements in the environment, their meaning and their status in the near future [4]. More specifically, the design of the system has to be in a way that facilitates the flow of information from the different technical elements to the operator and support his understanding of the situation [5, 6]. From this perspective, in order to facilitate operator awareness, excavator viewing aids need to be configured and designed in a way that optimally supports operator information acquisition. This applies to support for the primary excavating tasks (e.g. digging) and also for monitoring the surroundings to avoid collisions (e.g. during reversing or rotating movements).

### 2.2 Standards on Visibility and Viewing Aids in Excavators

According to Machinery Directive 2006/42/EC [7] with its binding character for machine manufacturers and distributers in the European Union, visibility conditions must be such that the operator can move the machine in complete safety for himself and exposed persons. Inadequate direct view must be compensated by appropriate devices providing the operator with indirect view on the surroundings of the machine. As explained by European Commission [8] this can be established by means of mirrors or CMS (i.e. closed circuit television, CCTV).

Further specification comes from EN ISO 474-1 [9] on general safety requirements for earth-moving machinery, which refers to ISO 5006 [10] on visibility performance criteria. This standard allows a total number of three to nine maskings (i.e. “blind spots”) of varying width at a distance of 12 m around the machine. At a distance of 1 m, no masking of more than 300 mm in width is allowed. Where these requirements cannot be met, additional mirrors or CMS can be employed for which requirements are listed in ISO 14401 [11] and ISO 16001 [12], respectively. However, a recent decision by the European Commission [13] concluded that these performance criteria fail to meet the essential health and safety requirements provided by Machinery Directive 2006/42/EC. Consequently, a revised version of ISO 5006 is expected for publication in the near future.

### 2.3 Empirical Evidence on Information Acquisition in Mobile Machinery

Much work has been done with regard to ergonomics, occupational safety and health when working with construction machinery (e.g. cabin proportions, zones of comfort and reach, vibration and noise), of which body and head posture can be related to visual information acquisition. When operators turn their head or body to attain a more favorable viewing angle, awkward postures can result, a relationship that has been described with regard to mining vehicles [14], backhoes and excavators [15] and construction equipment in general [16]. However, awkward body posture can also result from factors other than poor visibility, such as position of seats or controls.

Methods for objectively assessing visibility from the cabin and obstructions by parts of the machine (i.e. “blind spots”) have been applied to different types of mobile equipment, such as in mining machinery [17], and loaders and excavators [18]. To investigate how operators acquire visual information during regular and dynamic work activities in a real environment, Eger et al. [14], used eye-tracking in load-haul-dump vehicles in underground mining. The authors could show that, regardless of the direction of travelling (e.g. driving backward), glances were concentrated on a few relatively unobstructed areas around the machine, while other (important) areas were neglected. Similarly, Hella et al. [19] observed that operators of graders and other mobile machinery mostly attended their respective tool or equipment, even when appearance of pedestrians around the machine was quite frequent.

Fukaya et al. [20] investigated eye-movements of subjects in a simulated excavator task in virtual reality, but did not include viewing aids in their analysis. These authors found that glance duration on parts of the machine accounted for over 70 % of total dwell time, while glance duration on the surroundings was only 20 %. Similar results were obtained in a second study in which four experienced operators completed work cycles of loading a truck both in simulated virtual reality and with a real excavator in an outdoor environment [21]. Here, the authors reported more horizontal eye-movements during swinging as compared to other movements, such as loading the bucket, which could be related to visual information acquisition for prevention of collisions. Details on viewing aids (i.e. mirrors and CMS) and reversing movements were not reported.

However, to assess, develop and select suitable viewing aids and other technologies (e.g. person identification systems) that optimally support operators for critical maneuvers and thus prevent accidents, evidence on operator visual information acquisition is needed. Therefore, this study investigated operators' utilization of viewing aids and direct sight during excavator operation. This was accomplished by means of eye-tracking and observation during regular work on real construction sites. As a first step, utilization of mirrors, CMS monitors and direct sight was analyzed during reversing movements of the excavator.

## 3 Methods

### 3.1 Sample

Nine sites of five local civil engineering construction companies were visited, each with a different operator and excavator (see Table 1). Measurement duration was between 3 and 5.5 h (M = 4.2, SD = 0.8; Table 1), excluding regular breaks and all pauses related to setting up and calibrating of devices. Sites differed regarding their surrounding conditions, such as the amount of co-workers, machines, obstacles and passersby on or around the workspace.

The sample comprised crawler and wheeled excavators of different manufacturers with a length of 8.2 to 10.7 m and a mass of 17 to 32 tons. Only regular attachments (i.e. hoes and grabs) were used for typical work activities, such as trenching, grading, sloping, pipe-laying, object transport, and loading and spreading of material (including loading of trucks).

In all machines direct sight from the cabin to the rear area was obstructed by the counter weight and direct sight to the right side was partly obstructed by the boom. All machines were equipped with a CMS depicting the area directly behind the machine on a monitor in the cabin, one left rearview mirror and one, two or three right rearview mirrors. Four excavators had an additional camera displaying the right side of the machine on the monitor (with split screen). No excavator had mirrors installed on the counter weight of the machine. Configuration and adjustment of all mirrors and CMS were in accordance with regulations and corresponded to what operators were used to working with for at least one year.

Operator mean age was 41.5 years (SD = 13.1), reported professional experience with excavator operation was 17.3 years (SD = 8.8). Operators (all males) were road

**Table 1.** Characteristics of machinery, operators and work activities (abbreviations: LS = loading and spreading of material, G = grading, T = trenching, S = sloping, OT = object transport, PL = pipe-laying)

| Site no. | Excavator type and attachment | Operator age and years of experience | Measurement duration (h) | Excavator operations |
|---|---|---|---|---|
| 1 | Crawler; trench cleaning bucket, hoe | 47 (6) | 4 | LS, G |
| 2 | Wheeled; trench cleaning bucket, hoe | 38 (3) | 5 | LS, T, OT |
| 3 | Wheeled; hoe, grab | 56 (25) | 5 | LS, T, S, OT |
| 4 | Crawler; hoe | 38 (12) | 3.75 | LS, G |
| 5 | Crawler; hoe | 51 (27) | 3 | LS, T, PL |
| 6 | Wheeled; hoe, grab | 58 (25) | 5 | LS, T, OT |
| 7 | Crawler; hoe | 26 (11) | 3 | LS, G, T, OT |
| 8 | Wheeled; trench cleaning bucket, hoe | 36 (22) | 4.75 | LS, G, S |
| 9 | Crawler; trench cleaning bucket | 53 (25) | 4 | LS, G |

builder, car or construction machinery mechanic, engine fitter or construction builder by formal training.

### 3.2 Apparatus

Eye-movements were measured using a head-mounted eye-tracker “Dikablis” (Ergoneers GmbH, Manching, Germany) with a sampling rate of 25 Hz, scene camera field of view of 120°, four point calibration, contrast pupil detection and D-Lab 3 (Ergoneers GmbH, Manching, Germany) as recording software. A laptop computer was stored behind the operator and connected to the eye-tracker in such a way that operator head and body movements were not limited. Exiting the cabin was possible at all times by disconnecting the eye-tracker, and data recording resumed after reconnection.

Simultaneous to eye-movement recording, excavator operations were observed and category coded using a tablet computer and a software tool with buttons for each category [22]. Additionally, operations were video recorded using a GoPro Hero 3® for subsequent correction of observational data, if necessary. Information on site and machine characteristics, as well as demographic data and operators’ experience with viewing aids were gathered by guided interviews.

### 3.3 Procedure

All sites were visited on two consecutive days. During the first visit a trial measurement was conducted to let operators get accustomed to the measurement devices. Importantly, the purpose of the study was described in broader terms (i.e. to improve cabin design) so as to minimize behavioral adaption. Written informed consent was obtained from operators and all other involved personnel. Main measurements on the second visit started in the morning and lasted until the early afternoon or until the end of the shift. Eye-tracking and activity observation were done continuously, while battery change and recalibration of the eye-tracker were done at convenient moments so as to interrupt work processes as little as possible. After measurements operators were interviewed and were thanked with a small present.

### 3.4 Data Preprocessing and Analysis

When necessary, observational data were corrected manually and frame by frame by using video recordings of work activities and Noldus Observer® XT 12 (Wageningen, The Netherlands) coding software. As an excavator's upper structure can turn over 360°, direction of travelling can be ambiguous. Therefore, movements were regarded reversing movements when direction of the cabin was opposite to direction of travelling with a tolerance of ±45°. This criterion was applied for a period of 15 s before, until the end of the movement. For subsequent eye-movement preprocessing and analysis, reversing intervals were defined, each including one reversing movement of the excavator plus a period of 4 s previous to the start of the movement.

Eye-movement data was processed using D-Lab 3. During intervals, incorrect pupil position was corrected frame by frame and manually. Further, glances on four different areas of interest (AOI) were coded frame by frame and manually, and according to [23]. The first three AOI related to viewing aids for indirect sight, namely the CMS monitor, the left mirror, and the right mirror(s). The fourth AOI was defined as the area next to and behind the machine, which could be seen directly when operators rotated their head ("look over the shoulder", defined as all glances on surroundings for which combined operator head and eye movements exceeded a 90° turn to either side).

As a measure of utilization of AOIs, percentage of intervals with one, two, more than two, or no glances at all was calculated. As a second measure, percentage of intervals with glances on each AOI was calculated, both over the aggregated sample and individually for each construction site.

## 4 Results

### 4.1 Description of Reversing Movements and Glances on AOI

During measurements, a total number of 415 reversing movements were observed (M = 46.1, SD = 25.5). Movement duration was 5.4 s on average (SD = 6.2), with a skew to the right (i.e. there were more movements with shorter duration) and median of 4.0 s. Taken together, all movements summed up to 2236.3 s (37 min and 16.3 s).

During reversing intervals, a total of 1006 glances were counted on all four AOI (i.e. CMS monitor, left mirror, right mirror(s) and rear area by head rotation).

## 4.2 Percentage of Intervals with Glances on AOI

As a measure of utilization of different viewing aids, amount of attended AOI per reversing interval was counted. Figure 1 shows that in 12.3 % of all cases, there was no glance on any AOI, while in 37.1 %, glances on one AOI were found. In the majority of intervals (42.2 %), glances were found on two different AOI and in 8.4 % of all intervals glances on more than two different AOI were found.

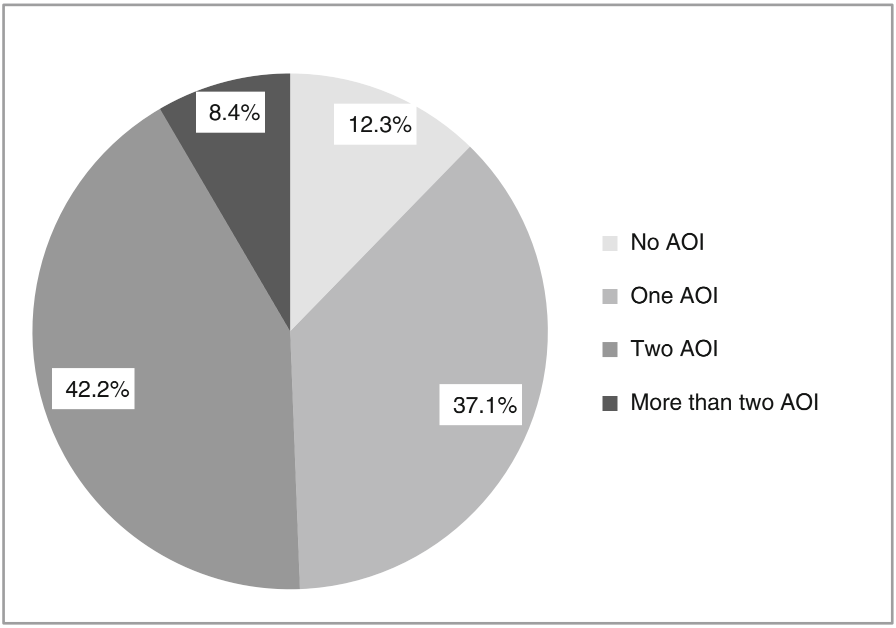


**Fig. 1.** Amount of AOI that were attended during intervals in percent

In a next step, percentages of reversing intervals with glances on each AOI were calculated. On an aggregate level, glances on the CMS monitor during intervals occurred in 56.9 % of all intervals. Similarly, glances on the left mirror occurred in 64.1 % of all intervals, while glances on the right mirror(s) were found in 7.2 %. Glances on the left and right rear areas by rotating the head (i.e. "look over the shoulder") were found in 19.3 % of all intervals (Fig. 2).

Similarly, glances were calculated for individual construction sites. Results revealed variations of the aggregated values as shown in Table 2. For instance, utilization of the CMS monitor varied between 10.4 % and 98.2 % (site No. 9 vs. No. 6). Similarly, utilization of the left mirror varied between 23.1 % and 100 % (site No. 3 vs. No. 6).

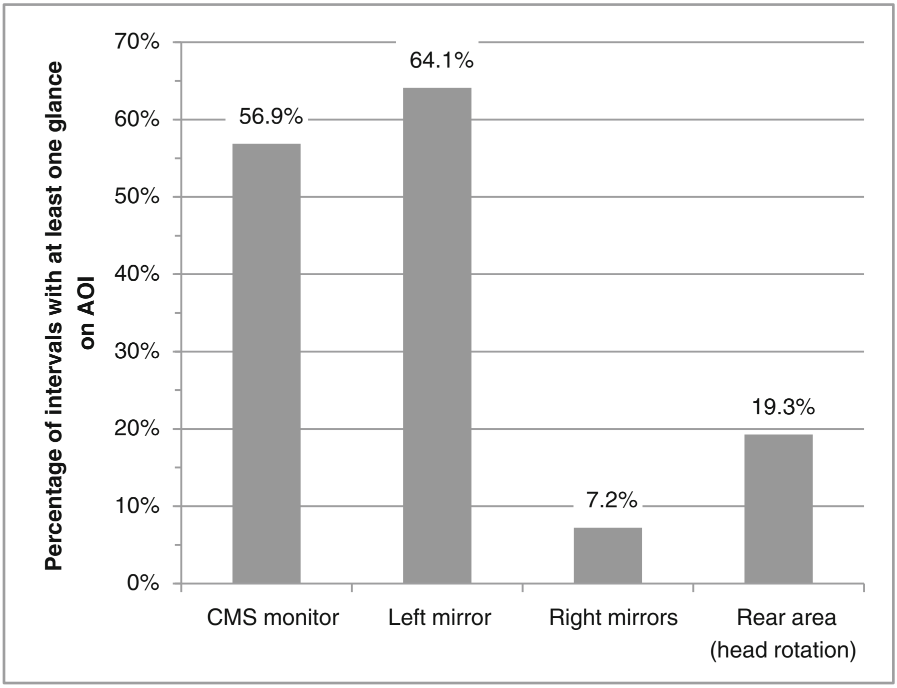


**Fig. 2.** Percentage of intervals where at least one glance on an AOI occurred. For variations, see Table 2.

**Table 2.** Percentages of intervals with glances on an AOI during intervals for each site

| Site no. | Number of intervals | Intervals with glance on AOI (in % of all intervals) | | | |
|---|---|---|---|---|---|
| | | CMS monitor | Left mirror | Right mirror(s) | Rear area (head rotation) |
| 1 | 50 | 68.0 | 74.0 | 2.0 | 18.0 |
| 2 | 21 | 85.7 | 90.5 | 57.1 | 19.0 |
| 3 | 26 | 26.9 | 23.1 | 19.2 | 61.5 |
| 4 | 96 | 56.2 | 55.2 | 1.0 | 21.3 |
| 5 | 48 | 66.7 | 68.8 | 0 | 2.1 |
| 6 | 55 | 98.2 | 74.6 | 0 | 5.5 |
| 7 | 24 | 50.0 | 45.8 | 12.5 | 20.8 |
| 8 | 18 | 94.4 | 100 | 22.2 | 11.1 |
| 9 | 77 | 10.4 | 62.3 | 5.2 | 26.0 |

Glances on the right mirror varied between 0 % and 57.1 % (site No. 2) and those on the rear area varied between 2.1 % and 61.5 % (site No. 5 vs. No. 3).

# 5 Discussion

## 5.1 Summary and Implications

Many accidents with excavators are related to insufficient operator sight from the cabin to the areas around the machine, so that humans or objects in the vicinity cannot be seen properly. Mirrors and camera monitor systems are intended to support operators to gain an understanding of the surroundings. However, little is known about how operators acquire visual information during regular work, which is an important aspect for assessing, developing and selecting viewing aids and other technologies (e.g. person identification systems). Therefore, operator utilization of information sources for reversing movements was investigated under real conditions by means of eye-tracking in combination with observation of work activities. Results showed that operators engage in active search for information relevant for reversing. However, the finding that multiple sources were used for about half of all reversing movements suggest that utilization of only one information source may not always be sufficient. Eye-movement analysis on an aggregate level further showed that all viewing aids, especially the left mirror and the CMS monitor, were used for reversing. Analysis of individual construction sites revealed variations of these aggregate values. Results can be used to further develop methods for accident prevention on construction sites.

For reversing movements, especially the left mirror and the CMS monitor were used. This emphasizes their relevance for operators gaining an understanding of the rear areas and thus for prevention of accidents when reversing. Both viewing aids may also be important for achieving operator Situation Awareness as they can be helpful to identify elements in the environment (i.e. humans or objects), understand their meaning and predict their status in the near future. However, there are other modalities (i.e. auditory or haptic information) and other sources of information (i.e. short term and long term memory) that contribute to Situation Awareness. To fully explain how Situation Awareness is achieved for the operation of excavators a more in-depth investigation would be necessary.

Results showed that operators used the CMS monitor and mirrors and also turned their head to look directly at lateral and rear areas. This may point towards an information need that could not be met by using viewing aids only or direct view only. It is possible that information sources served different functions during reversing movements. As the CMS monitor displays the area directly behind the machine, it may have been attended primarily for checking for obstacles prior to the movement. Other information sources, like the mirrors or direct view may provide better information on relative distances between the machine and objects and may therefore be used for maneuvering during longer movements.

Although information sources (i.e. viewing aids and rear area) were used for many reversing movements, it should be interesting to analyze cases where these sources were neglected. Further analyses may reveal common characteristics of these cases, such as effects of personal preferences, habituation or training. Further, it can be assumed that the type of work activity (i.e. object transport vs. grading) influences information acquisition behavior. Similarly, situational factors, such as confined spaces or the amount of people and machines on site contribute to operators' utilization of viewing aids. However, situational factors could not be controlled in this study and thus varied across our measurements.

As another important factor, the design of viewing aids should be mentioned because this, too, influences how operators use mirrors and the CMS monitor. For example, viewing aids' display quality, position, size and field of vision can be regarded important as these can determine their relative distance to the operator and the size of displayed elements (e.g. a human). Improvements regarding these aspects may not only lead to increased utilization, but could also enhance perception and understanding of attended information and, finally, drive behavioral adaption that increases safety when moving with excavators.

It is important to note that eye-movement analysis can reveal central, but not peripheral visual information acquisition. However, it cannot be ruled out that peripheral vision plays a role in information acquisition when operating excavators. Furthermore, reversing intervals included a reversing movement and a period of four seconds before the start of the movement. It should be interesting to investigate periods preceding these intervals as they may contain information acquisition behavior that has yet to be analyzed.

It should further be noted that observation or the eye-tracker may have caused reactivity in operators. To avoid this, trial measurements were completed by all participants so as to get accustomed to the measurement devices. Further, the purpose of the study was not disclosed until the end of the measurements. Also, operators were assured that no evaluation of their work would take place and that all data would be analyzed anonymously. Finally, measurements lasted quite long, so that after some initial behavioral adaption operators may have returned to their every-day working style.

## 5.2 Conclusion

Eye-tracking and task observation were used in a field study to investigate whether, and how excavator operators used viewing aids for reversing. Operators actively engaged in search for relevant information for reversing movements. In many cases, one or more viewing aids were used, and especially the left mirror and the CMS monitor which emphasizes their importance for the safe operation of excavators. Cases of neglect of viewing aids may be explained by differing task demands or by situational factors, and can be useful for evaluation, selection and development of viewing suitable viewing aids. Improvements could eventually lead to higher levels of utilization, understanding and safer behavior, and may thus help reduce accidents with excavators.

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