



# Article Perception of the Harvester Operator's Working Environment in Windthrow Stands

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Abstract: The aim of the study was to determine the mental workload of a harvester operator when working in late thinning and in windthrown stands of the same type and age, using eye movement patterns as an indicator. Eyeball movement variability was analysed using the eye tracking method. The mean duration of eyesight fixations in windthrown stands was shorter than in the control undamaged stands by about 20% (444 ms and 534 ms, respectively). The mean time of eyesight movements (saccades) in the windthrown stands was shorter than in the control undamaged stands by approx. 15%. The largest differences between the duration of saccades in the windthrown and control stands were observed between the cutting of trees and cutting logs off their root plates: the saccades were longer by about 20% when working in the control stands (49 ms) as compared to the windthrown stands (43 ms). Large differences in the duration of saccades between the windthrown area (42 ms) and the control area (47 ms) were also found when travelling between successive operation sites. In both types of stands, the shortest saccades were observed during processing: 39 ms. Summary durations of saccades observed during the processing of successive trees occurred in sequences showing repeated periods of variable eyeball activity, where longer saccades were followed by shorter ones. Documented more variability of eyesight activities of the harvester operator performing the operations of processing and moving is new standard of eye balls activities for the more taxing work conditions presented by windthrown stands.

Keywords: timber harvesting; post-disaster; mental workload; eye-tracking; ergonomics

## 1. Introduction

Catastrophic wind damage occurred long before the beginning of human interference in natural forest ecosystems. Windthrow events have always been an important process in the forest environment and often a necessary regenerating force that affected the variability and diversity of forests [1]. In temperate regions, winds have a dominant role among all weather phenomena. Together with insect outbreaks, floods, fires and droughts, winds are among the most important natural phenomena that change ecosystems [2]. The first official records of catastrophic wind damage appeared in Europe in the nineteenth century. In Poland, one can find reports about four hurricanes striking the Piska Forest at that time. About 130 hurricanes have been recorded in Europe since the mid-20th century, with an average annual damage to forests estimated at about 35 million m<sup>3</sup> of timber [3,4]. In mountain areas, a noticeable increase of wind damage was observed right after World



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). War I. For example, in 1920, a windthrow event in the Sudetes exceeded the five-year prescribed harvest. Today, wind damage is considered the consequence of the inadequate forest management practices introduced in the 19th century, which led to the establishment of even-aged monocultures, especially vulnerable to natural disturbances [5]. However, the large-scale catastrophic damage experienced in recent years is certainly related to the increasingly frequent and violent weather events, possibly derived from the growing global temperature [6–8]. Since 1990, several hurricanes have been recorded in Europe, including: Vivian and Wiebke (120 million m<sup>3</sup> of windthrown timber), Lothar (200 million m<sup>3</sup>) and Kiryll (64 million m<sup>3</sup>). Most likely, the frequence and violence of such events will continue to increase [9–12]. In northern Poland, enormous damage was recorded in the summer of 2017, when heavy wind storms totally destroyed an area of 120,000 ha. The damage was estimated at almost 10 million m<sup>3</sup>, and over 39,000 ha remained in the need of complete forest regeneration. That was the largest forest damage event in the history of Polish forestry.

Salvage harvest of damaged timber is the primary task of forest services. This task is extremely challenging when it comes to work safety and productivity. High accident risk derives from the production of timber with characteristics that are nonstandard and difficult to evaluate [13]. Furthermore, timber harvesting in windthrown stands offers particularly difficult conditions when it comes to moving, setting a safe work sequence and minimizing additional value losses. There is a huge diversity in the forms of wind damage, all hiding some danger: lifted root plates that may fall on the operators once severed from the stems, bent tree trunks that may snap suddenly and unpredictably when crosscut, broken trees leaning over other standing trees. Such exceptionally dangerous working conditions discourage motor-manual work, since chainsaw operators are fully exposed, with minimal protection [14]. Therefore, since the1990s, the use of harvesters has become the standard practice in windthrown stands [15–21]. By placing the operator inside a protected cab at a safe distance from the cut zone, the number and the severity of accidents recorded during timber harvesting in post-disaster areas has been reduced significantly [22–24].

Harvester work qualifies as partly-automated work, since travelling between work stations and felling trees require full operator participation, whereas wood processing is largely automated and the operator just plays a supervisory role. The StanForD control and measurement standard has been in operation since the 1980s, and allows easy exchange of automated working protocols [17]. However, partially automated work from a comfortable cab is only seemingly undemanding; in fact it generates a significant cognitive and psychological load on operators [25,26]. The monotony and regularity of external stimuli generate a slowly developing condition of reduced awareness [27], while the complexity of some tasks may cause mental fatigue and psychological stress. That may lead to specific accident hazard and to a general negative effect on workers' health [28,29]. Paradoxically, difficult working conditions, such as steep terrain in the mountains [30], or the heterogeneous nature of the salvage task in post-disaster areas, may mitigate the above-mentioned risks, at least to some extent. Therefore, the mental workload associated with work in postdisaster areas maybe peculiar, and somewhat different from that experienced under the conditions of regular cuts. The identification of the harvester operator's mental workload under standard and post-disaster conditions should be the starting point for designing safe and efficient technological systems and work routines. It is particularly important to determine the degree of difficulty of each task and correlate it with work efficiency, mental workload and fatigue, as characteristic of automated production processes applied to forestry. Therefore, the goal of this study was to gauge the mental workload experienced by harvester operators working in post-disaster areas and compare its level and variability with those experienced during conventional planned operations in undamaged stands of the same type and age.

#### 2. Materials and Methods

The study was conducted in south-western Poland, in the Rudy Raciborskie Forest District –the Regional State Forest Directorate (RDSF) of Katowice (Figure 1).



Figure 1. Research location: the Rudy Raciborskie Forest District.

In the summer of 2017, the area was hit by a hurricane that completely destroyed over 800 ha of forest and severely damaged an additional 1500 ha. The estimated wind-damaged timber volume amounted to 260,000 m<sup>3</sup>, which was almost three times the size of the planned annual felling. In the Solarnia Forest Range, where the research was carried out, the annual felling increased by 60,000 m<sup>3</sup> (Figure 2). For safety reasons and to obtain adequate work efficiency, harvesters and forwarders were used to clear the disaster areas. Overall, 20 such sets operated in the area.

In particular, study data was collected in forest compartments 411d and 410c (Table 1). In these compartments, 95% of the total damage consisted of windthrows, and only 5% of windsnaps. The analyzed stands grew in a flat area.

Before the work commenced, corridors were designated in typical parts of the analysed areas. Corridors had a total length of approx. 200 m each, were spaced 15 m apart and were placed both in the damaged areas and in the adjacent forest areas that had been left undamaged. In the damaged areas, corridors were set perpendicular to the wind direction, so as to allow for processing trees on the skid trails in front of the machine and on its sides. Each research plot corresponded to the area covered by a single corridor. Therefore, the study included two types of research plots: damaged and undamaged (i.e., control). A John Deere 770 harvester travelled along the corridors and processed trees into 2.5 m and 5 m long logs. In the undamaged areas, the harvester also performed felling. The technical characteristics of the machine are presented in Table 2. The machine was 7 years old, had clocked 14,000 machine-hours and it was in good technical conditions (Figure 3). Before starting work, the operator was properly instructed about work requirements, and in particular about safety procedures and log quality specifications. All work covered in this study was carried out by the same forty-five-year-old operator with 10 years' experience in mechanized harvesting jobs and 4 years' experience on this particular machine. The operator had no diagnosed vision disorders.



**Figure 2.** Disaster areas in the Solarnia Forest Range in 2017, Rudy Raciborskie Forest District, forest compartments 411d and 410c.

Location	Compartment	Area [ha]	Site Type	Species Composi- tion	Age [Years]	DBH [cm]	Height [m]	Merchantable Timber [m <sup>3</sup> ∙ha <sup>-1</sup> ]	Disaster [%]
Solarnia F.R.	411d	3.65	Humid mixed forest	Pine 40% Pine 30% Alder 30%	22 28 28	10 15 12	9 15 12	32 42 28	50
Solarnia F.R.	410c	3.15	Humid mixed forest	Pine 60% Pine 20% Pine 20%	33 33 33	17 17 16	15 16 15	77 12 19	50

 Table 1. Forest appraisal features in forest compartments 411d and 410c under analysis.

Table 2. General technical data of the John Deere 770 D harvester.

Parameter	Value		
Weight [t]	11.55		
Dimensions: length/width/height [m]	5.91/2.45/3.62		
Crane: type/range [m]	John Deere 140H/7.9m		
Cutting head	Waratah H412		
Engine power (kW/KM)	140/190.35		



Figure 3. The John Deere 770d harvester during operation on a research plot [photo by K. Adamski].

During work, the harvester operator's eyeball activity was recorded with the use of the Tobii Pro Glasses 2 reflective eye-tracker (Tobii AB, CO) (Table 3) and the Tobii Pro Glasses Controller software installed on a portable computer [31]. Before starting the work, the operator was informed about the purpose of testing and the measurement method. The measurements started at 9 am, after a 60-min warm-up. After calibrating the glasses, the recording session began and the operator performed routine tree felling and bucking tasks.

Table 3. Technical data of the Tobii Pro Glasses 2 eye-tracker.

Eye-tracker					
Sampling frequency	50–100 Hz (in respect to eye-trackers the sampling frequency means the number of identified locations of fixation points per one second. This frequency determines the quality of results and the accuracy of measurements taken)				
Cameras	4				
Scene camera FOV	82° horizontally, 52° vertically				
Scene camera parameters	h.264; 1920 $\times$ 1080 pixels; @25 fps				
Field of view	160°				
Diagonal of scene camera FOV	90°; 16:9				
Sound recording	Yes				
Weight	45 g				
Battery	120 min.				
Recording Station					
Connection	HDMI, Micro USB, 3.5 mm Jack				
Frequency	2.4 GHz & 5 GHz band				
Dimensions	$130 imes 85 imes 27~\mathrm{mm}$				
Weight	312 g				

The recording sessions lasted approx. 40 min each. After each session, the data was automatically saved, the eye-tracker was calibrated again and a new session was started.

The measurements made it possible to obtain film material that was processed using the Tobii Pro Lab Analyzer version 1.102 software (Tobii AB, CO). The analysed videos allowed for distinguishing four work activities for which suitable measurement boundary points were defined. These were: Activity 1: felling—it started the moment the harvester head was positioned at the base of the tree stem and ended with the first passage of the cut stem through the feed rollers in the head (this activity was conducted only on the standard, undamaged research plots);

Activity 2: cutting off the tree stump—it started when the harvester head was positioned at the base of the stem to be cut and ended when cross-cutting was completed (this activity was conducted only on the damaged research plots);

Activity 3: delimbing and cross-cutting—it started with the first passage of the stem through the feed rollers in the head and finished when the tree top was cut off (on all research plots);

Activity 4: moving—it started the moment the machine moved from the current work station after discarding the top of the previously processed tree and ended when the machine had reached the next work station and the harvester head had been positioned at the base of the next tree to be cut (beginning of Activity 1 or Activity 2, depending on plot type).

The work recorded was smooth, with no breaks related to repairs, servicing or rest.

All recordings were scanned using the standard Tobii Pro Labi-VT filters [32]. The Attention Filter was applied in the configuration of snapshots and heatmaps. We used the Attention Filter because the recordings were performed in dynamic situations, where the operator was in constant motion. In this situation, a large variability of eyeball movements can be observed: fixations, saccades, smooth pursuits and VOR (vestibulo-ocular reflex). The Attention Filter in Pro Lab is essentially the Tobii Pro IV-T Filter, with the velocity threshold parameter set at 100 degrees/second instead of the default 30 degrees/second.

Based on the analysed film material, snapshots (individual film frames) were selected for the purpose of preparing heatmaps. Heatmaps were generated for the processing of randomly selected work batches containing five subsequent trees in both of the analysed stand types (i.e., damaged and control). For greater clarity, the heatmaps were generated in a simplified form. The original images were calibrated to snapshots with overlaid heatmaps using the Bentley Descartes software. The calibration was done by means of projective transformation with the use of 4 common points. The next step was to suppress the heatmaps and to vectorise the head with the accompanying elements in the photos. After vectorisation, the snapshots were suppressed and the heatmaps were brought back, obtaining the effect of a vector model being superimposed on the heatmap. The conversion of the coloured image to gray scale was done in Adobe Photoshop.

On the snapshots described above, we designated five areas of interest (AOIs) as follows: AOI 1 = the harvester crane and head; AOI 2 = the stem being processed; AOI 3 = the log storage area; AOI 4 = the felling site; AOI 5 = stand and corridor. We scanned the films with the fixation filter configured as "standard" in Tobii Pro Lab, with the following settings: gapfill-in (interpolation) = disabled; eye selection = average; noise reduction = moving median; I-VT fixation classifier = threshold 30 degrees/second; max. time between fixations = 75 ms; max. angle between fixations = 0.5 degrees; minimum fixation duration = 60 ms. Fixations were noted individually in relevant AOIs for the whole footage.

The research into the operator's eye activity during a work shift (the length of fixations and saccades), considering AOIs and the analysed stands, was conducted based on data generated in the Tobii Pro Lab software: metrics and raw data. In view of the oblique distribution of fixation durations, the significance of differences of the median of the analysed variable was determined based on the Kruskal-Wallis non parametric test.

The variability of the duration of fixations observed during the harvester's operation was determined by presenting the measurement data as a time series, i.e., a sequence of observations of a given variable as a function of time [18,33]. The harmonic structure of the series (i.e., observed sequence of saccades) was determined using the autocorrelation function, after prior logarithm transformation of the original data. The variability of successive, consecutive sums of saccade durations during work on one tree was defined as

the mean value of the indicators of variation of saccade durations observed during work on the previous and the next tree (1).

$$S_{nm} = \frac{a_{x-1} \times 100}{a_x} \tag{1}$$

where:

S—indicator of variation of saccade durations [%] n—activity (p—processing, m—moving, c—cutting), m—stand category (s—standard stand, p—post-disaster stand),  $a_x$ —sum of saccade durations during work with a tree [ms]

## 3. Results

The analysed study material included over 5000 s of recordings in damaged stands and approx. 30,000 s of recordings in undamaged, control stands. Heatmaps were generated on the basis of over 1500 fixation points. Analyses of the duration of saccades and fixations were performed for the entire database, within the selected AOIs: 219 complete cycles in the damaged stands and 469 in the undamaged stands. In total, about 3500 fixations and saccades in the damaged stands and almost 25,000 fixations and saccades in the control stands were obtained.

The mean time of saccades in the damaged stands was significantly shorter than in the control stands (Figure 4, Table 4). Significant differences in the duration of saccades in the compared stands were also found between felling and cutting off the root plates.



Figure 4. The duration of saccades at the work station of the harvester operator.

 
 Table 4. Results of the U Mann-Whitney test: saccade duration in the damaged and undamaged stands.

Operation	Ζ	р
Total of all operations	-1.839	0.049
Cutting/Cutting off	-2.143	0.030
Processing	-0.510	0.610
Moving	0.714	0.470

In both types of stands, the shortest saccades were observed during processing (39 ms and 43 ms respectively). The main element of the operator's vision was the log being processed in the vicinity of the harvester head and the cutting device (Figure 5). When the

log being processed was moved from the right to the left side of the operator's field of view, over 50% of the saccades were located on the processed stem at the point of its cross-cutting (i.e., AOI 2). When the log was moved to the right side—which was less frequent—the same AOI 2 attracted only about 37% of the saccades. The remaining observations were evenly distributed between the harvester head and the place where the wood was stored (AOI 1, AOI 3).



**Figure 5.** Heatmap of the harvester operator's field of view during processing in the control and the damaged stands.

Large differences in the duration of saccades between the damaged area (42 ms) and the control area (47 ms) were found for travelling between successive operation sites. The field of view of the machine operator during this operation was definitely narrower in the damaged stands (AOI 5) (Figure 6). It covered an area with numerous root plates of windthrown trees, directly in front of the harvester on both sides of the crane. Under those difficult working conditions, more than 70% of saccades were concentrated on the access corridor. In the undamaged control stands, the operator searched for trees designated for felling, growing both in front of the cab and on both of its sides. Therefore, the operator's field of vision was wider and focused on the stand (approx. 50% of the saccades), on the processed wood (almost 30% of the saccades) and on the harvester head and crane (approx. 17%) (Figure 7). The wide field of vision was the result of the operator's eyeball activity as well as his head movements, which, however, was not analysed separately.



Figure 6. Heatmap of the harvester operator's field of vision during a run in the post-disaster stands.



Figure 7. Heatmap of the harvester operator's field of vision during a run in the standard stands.

The largest differences between the duration of saccades in the damaged and the undamaged control stands were observed for tree felling (Activity 1 - performed on undamaged plots) and for cutting stems off root plates (Activity 2 - performed on damaged plots) (Figures 8 and 9). During work in the control stands, saccades were longer by approx. 20% (49 ms). The operator's field of view basically covered the harvester head (AOI 1), on which almost 70% of observations focussed, and the tree trunk at the place of cutting and just below it (AOI 2) (approx. 20% of the saccades). Only about 10% of observations were connected with felling site (AOI 4). Cutting stems off root plates in the damaged stands was usually done in such a way that the place of cutting remained invisible to the operator, therefore he mainly observed the harvester head (approx. 40% of the saccades) and the processed wood (approx. 37% of the saccades) (AOI 1, AOI 2).



**Figure 8.** Heatmap of the harvester operator's field of view during tree cutting in the undamaged stands.



**Figure 9.** Heatmap of the harvester operator's field of view while cutting stems off root plates in the damaged stands.

The average eye fixation duration in the damaged stands was shorter than in the control stands by approx. 20% (444 ms and 534 ms, respectively). This difference was statistically significant (Figure 10). The coefficient of variation of the fixation duration was 68% for the control stands and 75% for the damaged stands. We observed a lower variation in the eye fixation length in the damaged stands, where half of the observations fell within the 200–600 ms range. However, the share of outliers was higher in this group.



Figure 10. Positional statistics of the fixation time in the damaged and undamaged stands.

The summary duration of saccades, within activities observed during the processing of successive trees, occurred in sequences showing repeated periods of variable eyeball activity (Figure 11). As a rule, longer summary times of saccades were followed by markedly shorter ones.



**Figure 11.** Sequence of saccades in the damaged and undamaged stands during felling (**A**), processing (**B**), moving (**C**).

The mean difference between the duration of subsequent saccades for all of the analysed activities amounted to 31% in the undamaged control stands, while in the damaged stands it was 94%. The variability of the sums of saccade duration observed during the processing of successive trees was determined in accordance with the formula no. 1. Their high differentiation between the analysed stands could be observed especially in the case of processing in post-disaster stands (Spp = 207%). For processing, the presence of significant second-order and fourth-order autocorrelations was also established, which proves that a longer saccade was clearly followed by a shorter one (Figure 12).



Figure 12. Autocorrelation function of the time series of saccades observed during processing in the damaged stands.

Harvester runs were characterised by similar variability of saccade cycles on both plots: Sms = 55% in the undamaged control stands and Smp = 50% in the damaged stands. The variability of saccade cycles calculated for tree cutting in the undamaged stands was higher (Scp = 25%) than for cutting off root plates in the post-disaster stands (Scs = 15%).

#### 4. Discussion

The evaluation of any harvesting technology should take into account economic, ecological and ergonomic factors [34–37]. Productivity is no longer regarded as the main evaluation criterion, and the ergonomic assessment of work tasks is gaining special importance. Years ago, such assessment concerned mainly the physiological workload associated with manual labour. Today, the affirmation of automated technologies has removed hard manual work and has transformed much of an operator's task into supervising the operation of a system. Thus, ergonomic analyses currently include also the tracking of changes in the human psyche because modern forms of work require complex thought processes and entail a significant cognitive workload.

The introduction of harvesters and forwarders in forestry meant that their operators developed forms of fatigue typical of mental work and characterised by a reduced capacity for concentration, impaired thinking, slowed and weakened perception, decreased motivation to complete the job, emotional disorders, focus on rest. Grzywiński and Hołota [27],

Sullman and Gellersted [28], Berger [29], who studied the mental workload of forest workers, pointed out that the job of the harvester operator involves mostly mental effort with very high levels of mental stress. Häggström et al. [38] noted also a high level of automaticity in the work of harvester operators, including the recognition of familiar, small objects without significant visual involvement [39]. The visual standard for the cognition of reality, namely eye tracking, is often used in neurobiology, psychology, marketing and computer science [40,41]. In forestry, the eye tracking study technique has been introduced in the last few years only [38,42]. Among other things, such studies probe the significance of recognising objects, planning tasks and establishing priorities, as well as top-down and bottom-up cognitive processes [43]. For simple and clearly defined tasks there is a high correlation between eyeball movement and mental stress [44,45]. The making and changing of decisions are closely linked to changes in eyeball movement patterns [46–48].

Longer fixations can be associated with a more difficult cognitive process occurring during observation of a large number of objects or a phenomenon that is not fully recognizable [49]. Rayner [40] drew attention to the variability of information obtained by means of eyesight, and thus to the relativity of such assessments. In the current experiment, clear differences in the duration of eyesight fixations indicate probably a different nature of the operator's work in the standard and the damaged stands. Although the average duration of fixations was longer under the supposedly easier work conditions offered by the undamaged stand, the data collected in the damaged area contained many more outliers—i.e., much longer fixations. These probably occurred while maneuvering the machine and the harvester head for the purpose of allowing trouble-free and safe cutting of difficult-to-reach windthrown trees. Very similar results were obtained by Szewczyk et al. [42], who analysed the work of a harvester operator on steep slopes: performing tasks in difficult terrain also involved fixations that were longer and had greater variability of duration than recorded for the same work and operator on gentle terrain. In another similar experiment, Häggström et al. [38] compared the fixation times of a harvester operator working in a thinning and a mature stand. Here, the occurrence of longer fixations was observed in thinning stands as compared to mature stands, where work is more dangerous and more valuable assortments are obtained. All these studies concur in associating longer fixation times with the easier work entailed in routine tasks, when a visual model of task execution is not created at the beginning of the task, but is constructed on an ongoing basis [50]. Conversely, complicated vision scenes determine shorter fixations, as already indicated by Duchowski [41] and Molnar [51]. According to Rayner and Castelhano [52], the mean duration of a fixation is 260–330 ms., which is slightly shorter than in our research (between 400 and 500 ms). As found in our study, the occurrence of periodic extensions of fixation duration up to 1.5 s in the case of tasks characterised by high intensity is consistent with the results provided by Steinman [53].

Saccadic eyeball movements reflect changes in mental load, and thus in the level of stress [45,54]. Increased load conditions shorten the reaction time and cause a rapid shifting of the eyesight to another part of the vision scene. Again, that is the case of the studies by Szewczyk et al. [42] for a harvester operator working on steep terrain, and by Häggström et al. [38] for a harvester operator engaged with final cutting. The present study aligns with those findings, reporting a shorter (about 14%) duration of saccades in the damaged stand, compared with the undamaged stand. The greatest differences between the duration of saccades in the analysed stands were observed between tree cutting (undamaged stands) and cutting off root plates (damaged stands). In fact, while these two operations might be considered functionally equivalent (as they both aim at separating the stem from the roots), they are inherently different in their technical execution and the latter is undoubtedly more difficult than the former.

On both research plots, the shortest saccades were observed in the case of processing. As observed in our experiment, the pattern of visual scanning of the terrain with areas of interest located on the harvester head (up to 50% of saccades), is consistent with other analyses. In the study by Häggström et al. [38] most saccades (58%) occurred between

fixations located on the saw of the harvester head. This amounted to 23% more than the mean from the entire processing of the wood. That could indicate that the maximum mental stress of the harvester operator occurs during processing, when a considerable cognitive effort is required in an attempt to maximize value recovery. Decisions made during processing strongly impact operation profitability and are often crucial to financial success. The greatest dynamics of changes in the length of saccades, visible in our experiment, and their clear cyclic pattern characterise well the way in which that operation is performed. Most likely, shorter saccades are associated with the actual cross-cutting, while longer ones relate to the search for new tasks. Processing is the only fully automated operation performed by the operator. Interestingly, it is this operation that requires the greatest mental strain and generates the highest level of stress, likely due to its crucial impact on value recovery and financial gain. The high psychological tension observed especially in the post-disaster areas was probably what generated the variable length of the total duration of saccades observed during the processing of successive trees. Longer saccade durations following shorter ones were probably related to the operator's rest during activities that are not formal breaks, just after work burdened with considerable psychological tension. What is visible here is a system of specific breaks concealed within work, as described by Rosner [55] and Grandjean [56].

The long duration of saccades when the machine was travelling, especially in the undamaged stands, are consistent with the findings of Häggström et al. [38]. New findings that emerged as a result of our research concerned the scanning of the working space (the corridor and the stand). In the damaged stands, scanning was mostly restricted to the access corridor, probably due to more difficult working conditions. When the machine was travelling, the operator focused on the route and did not collect information about the stand and the next work station to the same extent as when working in the undamaged stand. The work pattern in which the harvester operator plans subsequent tasks before completing the current ones speeds up the work and makes it smoother [50]. According to Traschütz et al. [57] peripheral vision is used by the machine operator continuously in order to assess the machine's position and speed when travelling. This phenomenon was also evident in our experiment when the harvester was moving in the undamaged stands, in which half of the eyesight fixations during travelling included scanning of the surrounding stand.

### 5. Conclusions

Conducted with the eye tracking method, an analysis of the visual information reaching harvester operators can help probing the cognitive strain experienced under variable conditions. Comparing the duration and the variability of eyesight fixations and saccades may enable a fair assessment of the cognitive workload imposed on a harvester operator by work in damaged and undamaged stands. Such indicators point at the significantly higher cognitive demand required by work in damaged stand. High mental loads borne by operators working on post-disaster plots affect the way they work while processing subsequent trees. They compensate for the high stress by cyclically unintentionally slowing down the most strenuous activities. Furthermore, within a complex task, eye tracking helps emerging those specific task elements where cognitive demand is higher, thus indicating where remedial action should be prioritized. That way, new and adapted work standards could be developed that take into account the challenging work conditions offered by windthrown stands. Development of such new standards may have a strategic value, given the expected rapid increase of storm damage events across Europe. An objective evaluation of cognitive stress may also help assessing harvester operators' mental resilience, and predicting longterm productivity under especially stressful work conditions. Thanks to the optimisation of work techniques, this knowledge may also be used in harvester operator training.

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14 of 16

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