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WHITE PAPER



Eye tracking in human factors

Assessing cognitive abilities

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What are cognitive abilities?



Cognitive abilities are mental processes and skills needed to carry out any task. These abilities rely on fundamental cognitive processes such as paying attention to specific situations and environments, remembering, learning, and problem-solving. Understanding cognitive abilities is crucial in human factors as it helps design systems, tools, and environments that align with human cognitive strengths and compensate for weaknesses. This knowledge can be applied to improve safety, efficiency, and user experience across various domains, including workplaces, transportation, and technology interfaces.

Human factors research delves into how humans interact with systems—comprising products, tools, environments, or technologies—to optimize design and operation to improve human wellbeing, performance, safety, human-computer interaction, and overall system effectiveness. This white paper focuses on the core cognitive abilities underpinning human factors research and real-world applications.



Situational awareness



Decision-making



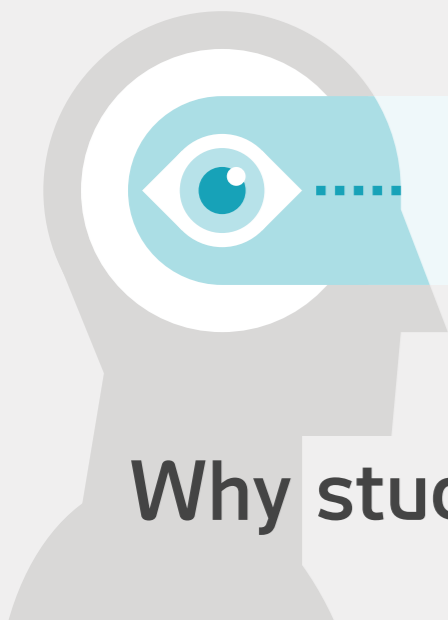
Cognitive load



Learning and skill acquisition



Team cognition



Why study cognitive abilities?

Mitigate human error

Identify and mitigate potential sources of human error by designing systems that align with human cognitive abilities.

Enhance workplace safety

Understanding how attention lapses lead to health hazards in a workplace can help reduce the risk of accidents.

Design intuitive interfaces

Studying cognitive abilities informs the creation of interfaces that are easy to navigate and the design of inclusive systems catering to diverse users.

Deliver effective training

By gaining insights into how people learn new tasks, training programs can be optimized to accelerate learning, improve retention, and transfer critical skills to new employees.

Improve cognitive load management

Studying cognitive load informs the design of interfaces that present information in a way that is easily digestible during high-pressure situations.

Optimize team performance

Research on team cognition helps build teams that communicate effectively and share a common understanding of tasks and goals, leading to better coordination in critical environments.

Who benefits from assessing cognitive abilities?

The insights of this white paper apply to a broad range of fields within human factors:

Healthcare



Aviation and space



Construction and engineering



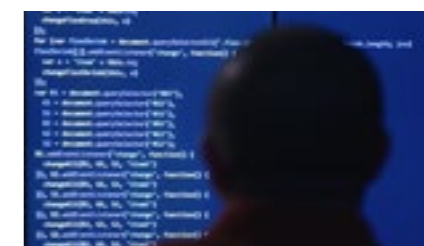
Manufacturing



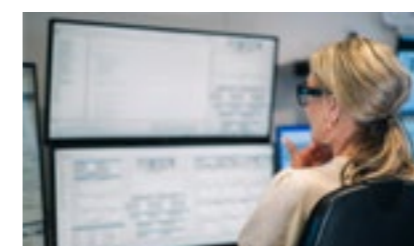
Automotive



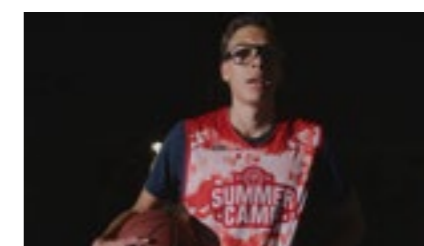
Computer science



Human-computer interaction



Sport performance



Eye tracking 101

Eye tracking is a sensor technology that measures and records the position and movement of the eyes. An eye tracker is a device for assessing where or what one is looking at, also known as the point of gaze.

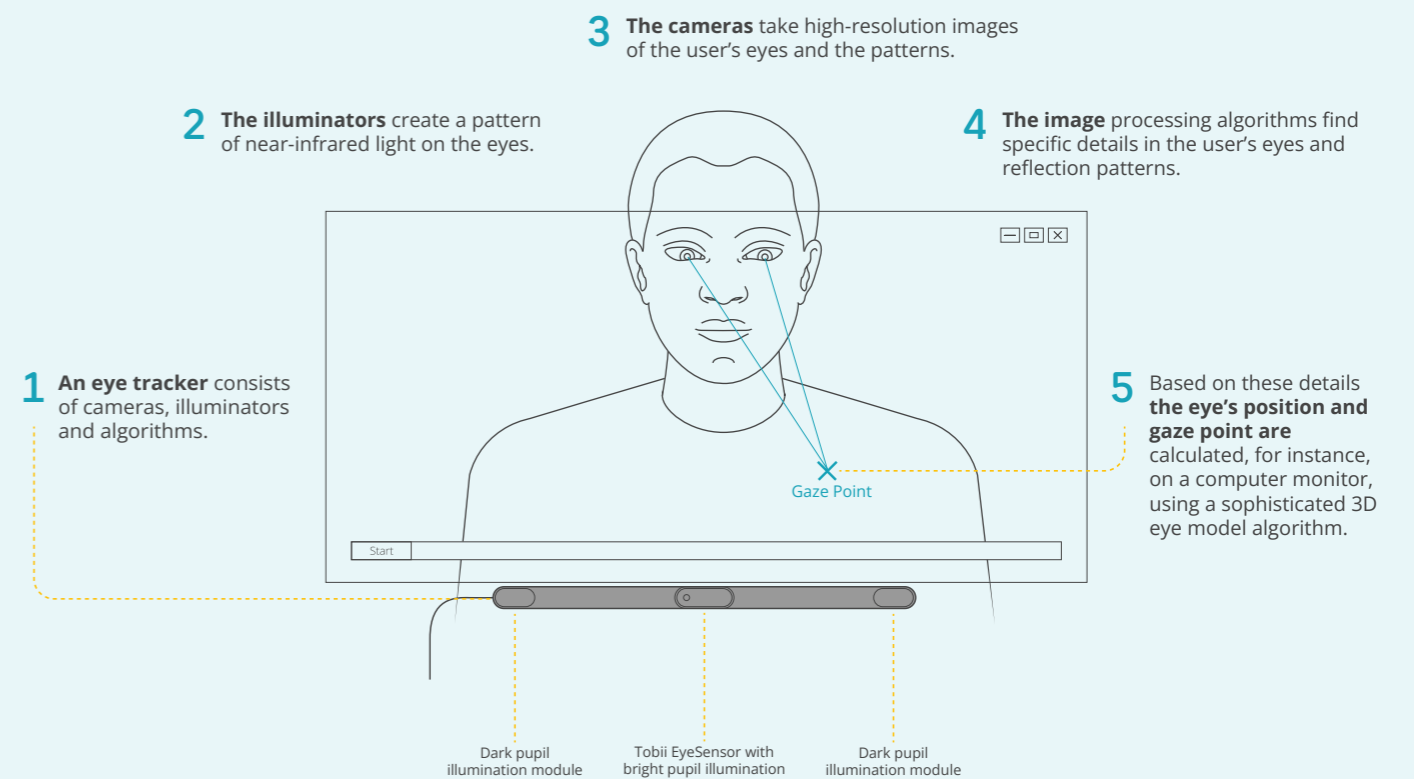
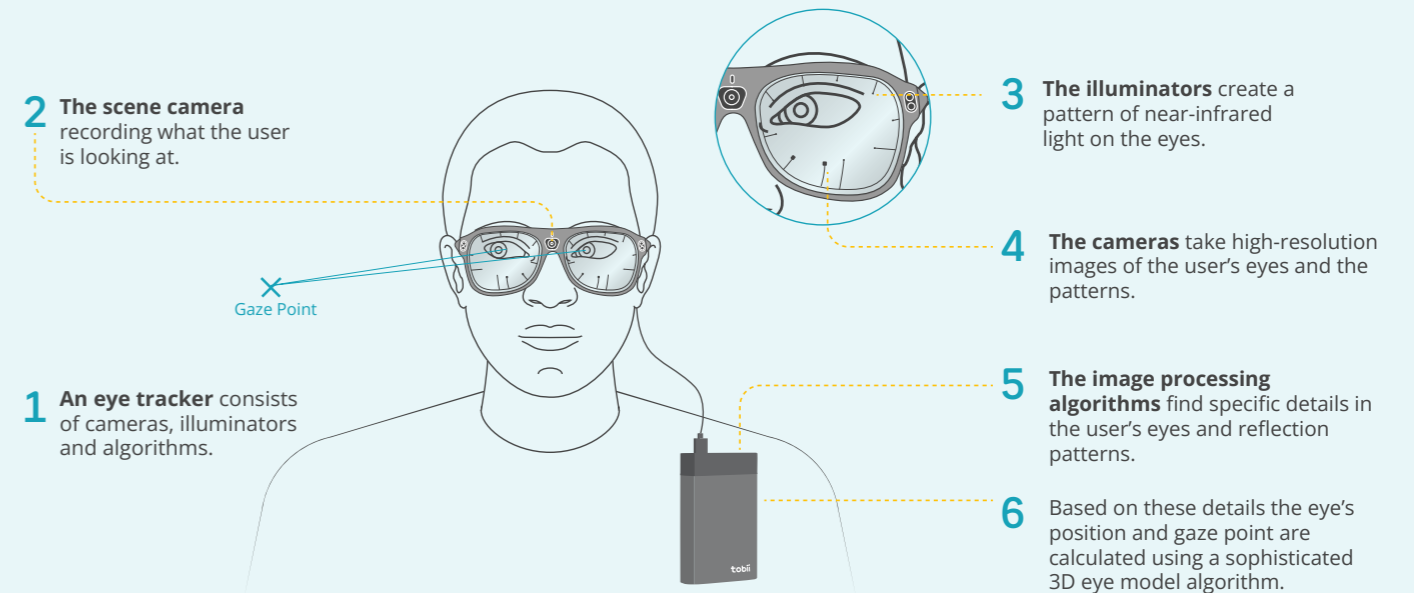
The point of gaze can be identified across various types of stimuli. Typically, an individual whose eyes are tracked directs their attention to a stimulus that may appear on a computer screen or in a real-world environment.

The value of eye tracking is based on the eye-mind hypothesis (Just and Carpenter, 1980), which proposes a close relationship between what one is looking at and what they are paying attention to at any given time. Tracking eye movements is a common way of measuring where people focus their attention. Although there are occasions when the gaze direction does not match what one is paying attention to, that is an exception rather than the rule regarding visual processing (Deubel and Schneider, 1996).

An eye tracker measures and records the point of gaze at different time points, allowing to classify some commonly observed types of eye movements, as well as other eye metrics:

- **Fixations** — a pause of eye movement while fixing gaze on a visual stimulus. Lasts for 100 to 300ms. During fixation, the visual system captures and processes the information about what is being looked at.
- **Saccades** — rapid, ballistic eye movements that align a person's eyes toward a new visual location. It occurs in between fixations and lasts 40 - 50ms.
- **Pupillometry** — the measurement of fluctuations in pupil diameter.
- **Eye openness** — a measure of the largest sphere that can fit between the upper and lower eyelids. It provides the basis for eyelid movement detection, including blinks.

Infographics explaining how wearable (top) and screen-based (bottom) eye tracker works.



Eye tracking study steps

1

Define study goals

Clearly define the objectives and questions the study aims to address. Determine what cognitive processes or behaviors you would like to address in your study.

2

Select participants

Decide on the target demographic for your study. Participants should represent your target population and be suitable for the research goals.

3

Select eye tracking equipment

Choose appropriate eye tracking technology based on the research requirements, such as eye tracking glasses or a screen-based eye tracker.

4

Prepare a stimulus or a task

Develop stimuli (e.g., images, videos, websites) or prepare a task relevant to the question you want to answer with your study.

5

Design experimental protocol

Plan the sequence of tasks or stimuli presentation for the study. Consider factors like task duration, order of presentation, and control conditions.

6

Conduct the pilot study

A pilot study is essential in various research contexts to ensure the feasibility of the research methods and procedures before conducting the main study.

7

Conduct the main study

Run the experiment as planned while recording the participant's eye movements with the eye tracking equipment. Monitor participants to ensure compliance with instructions and minimize distractions.

8

Data collection

Calibrate your eye tracker for each participant to maximize data quality and collect eye tracking data for all participants as they complete the tasks or view the stimuli. Ensure that data recording is done accurately.

9

Data analysis

Analyze the collected eye tracking data. Ready-to-use tools for eye tracking data analysis are available (e.g., Tobii Pro Lab), which can streamline the entire experimental flow, including data collection, eye movement classification, and data visualization.

10

Interpret results

Interpret the study's findings in the context of the research objectives. Draw conclusions about cognitive processes or behavior based on analyzing eye tracking data.

Sounds complicated? Explore our [Insight services](#) to help you with your eye tracking study, including data collection, analysis, and interpretation.

Situational awareness



What is situational awareness?

Situational awareness (SA) is knowing what is happening around you and determining where to focus attention to achieve one's goals. SA consists of a three-level hierarchical structure (Endsley, 1995):

- **Level 1: The perception of the elements in the environment within a volume of time and space.**

For instance, a pilot may observe an upcoming storm onboard weather radar and simultaneously notice the presence of another aircraft in the vicinity.

- **Level 2: The understanding of the element's meaning.**

The pilot acknowledges the potential hazards and risk posed by both the storm and the approaching aircraft.

- **Level 3: The projection of the element status in the near future.**

The pilot anticipates how the weather conditions might evolve and projects the trajectory of the approaching aircraft, estimating its speed, altitude, and intended flight path. Based on these projections, the pilot would make informed decisions regarding navigation adjustments.

Why measure situational awareness?

Safety and risk management

Maintaining optimal awareness of one's surroundings can help respond effectively to potential hazards or threats, thereby preventing accidents and minimizing risks in various human factors areas (Green et al., 2017; Sneddon et al., 2011).

- Inadequate nurse SA presents a significant patient safety issue, leading up to 60% of accidents costing patients' lives (Brady et al., 2013; Despina, 2018).
- Lack of appropriate SA is responsible for over 70% of maritime accidents (Hanzu-Pazara et al., 2008; Mccafferty and Baker, 2006).
- In the automotive field, most crashes occur due to the driver's failure to look at the right place at the right time (Lee, 2008).

Improved decision-making

SA enables better decision making by providing individuals with the necessary information to assess a situation accurately and choose the most appropriate course of action (Van de Walle et al., 2016).

Training and performance optimization

Monitoring SA allows organizations to identify areas for improvement and optimize performance (Green et al., 2017).

Team coordination

Teams with the highest performance tend to communicate more frequently and engage in

reciprocal transactions, particularly concerning reports related to SA (Sorensen and Stanton, 2016). Shared group SA is critical to improving preparedness for acute environmental emergencies and disasters (Laurila-Pant et al., 2023).

Why measure situational awareness with eye tracking?

Attention is the backbone of level 1 SA

The detection and perception of critical environmental elements are key components of Level 1 of SA. This process is closely tied to an individual's visual attention, which can be effectively measured using eye tracking technology. Indeed, eye tracking has demonstrated strong correlations with Level 1 SA (Zhang et al., 2023). In offshore drilling operations, 67% of errors occurred at the perceptual (level 1), 20% occurred at comprehension (level 2), and 13% occurred during projection (level 3) (Sneddon et al., 2011). This highlights the crucial role of timely and focused attention in enhancing SA in critical environments. Attention directs our visual focus to key elements essential for making informed judgments and maintaining SA (Caloca-Amber et al., 2024).

Objective and uninterrupted assessment

Eye tracking is the most commonly used physiological measurement to quantify SA (Zhang et al., 2023). It is a promising alternative to standard freeze-probe methods like the Situational Awareness Global Assessment Technique (SAGAT) or the Situation Present Assessment Method (SPAM) for assessing SA, providing real-time visual attention data without interrupting work tasks. It helps mitigate recall errors and human biases associated with self or observer-rating methods.

Correlation between eye movements and SA

Eye tracking metrics, including fixation rate, fixation count, and dwell time, correlate positively with SA (Hasanzadeh et al., 2018; Merchant et al., 2001; Paletta et al., 2017). These eye tracking metrics are better predictors of SA task performance than direct measurements, such as SAGAT. Visual sampling score is a quantitative score (expressed in %) used to assess SA by evaluating an individual's ability to monitor and respond to critical elements within a dynamic environment. A higher visual sampling score indicates a more effective and timely focus on vital task-related information, showcasing better situational awareness. It positively correlates with performance ratings and outperforms the correlation between performance ratings and SAGAT scores (de Winter et al., 2019).

Combine with other physiological measurements

User transition to higher levels of SA (levels 2 and 3) requires activation in the brain's inferior, middle, and superior frontal gyrus – the areas associated with cognitive functions, working memory, information processing, and comprehension. Brain imaging techniques, such as EEG, can help infer levels 2 and 3 of SA and can be paired with eye tracking that has established the relevant correlations with level 1 SA (Zhang et al., 2023).

How do experts study situational awareness?

Seafarer's situational awareness assessment with eye tracking technology

The study examined the relationship between seafarers' SA and attention allocation by examining visual patterns and eye movement metrics across simulated maritime piloting scenarios. Thirteen experienced seafarers participated in a bridge simulation while their eye movements were recorded with Tobii Pro Glasses 2. Based on the Situation Awareness Rating Technology (SART-2), the participants were divided into high and low SA groups. The simulation consisted of vessel departure, fairway navigation, encounters, poor visibility, and anchoring. The study results showed that seafarers with higher SA tended to focus more on external views, while those with lower SA focused more on electronic charts. Fixation and saccade metrics were significantly affected by SA levels in different Areas of Interest (AOI), confirming the relationship between seafarers' attention allocation and their SA. In specific scenarios like encounters and poor visibility, seafarers' SA levels correlated with fixation and saccade metrics in the AOIs. The study concludes that eye tracking technology can effectively measure and differentiate seafarers' SA levels based on their visual attention patterns in simulated maritime scenarios. It provides a foundation for cognitive abilities recognition and the establishment of cognitive competency standards for seafarers' screenings. Moreover, an easy and reliable way to assess seafarers' SA, such as with eye tracking, can help reduce human errors by rapidly detecting at-risk cognitive states.



AOIs in the ship pilotage simulations defined by the study authors (Jiang et al., 2021)

Scan path example of low SA group from Jiang et al. (2021) study.

Participants: 13 seafarers

Task: Bridge simulation (vessel departure, navigation in fairways, encounters, poor visibility, and anchoring)

Eye tracking hardware: Tobii Pro Glasses 2

Key finding: Eye tracking can effectively measure and differentiate seafarers' situational awareness levels based on their visual attention in simulated maritime scenarios.

Images were adapted from Jiang et al. (2021) under a Creative Commons Attribution License.

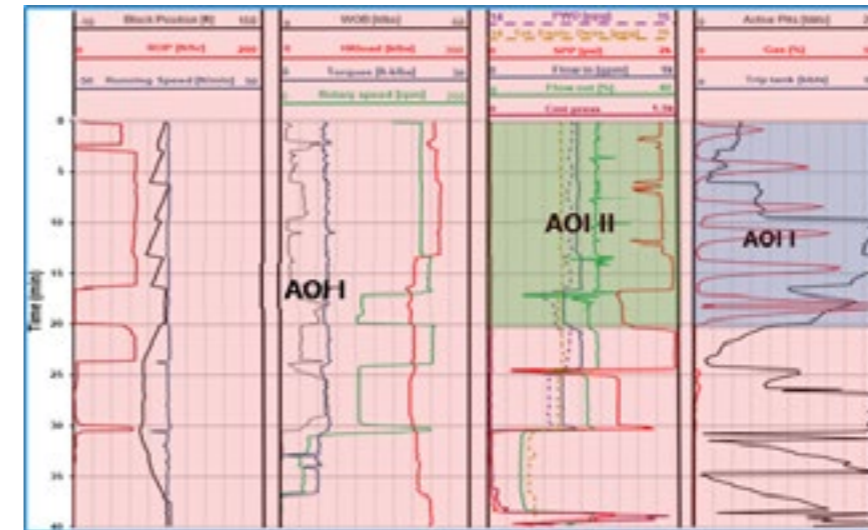
Cited publication:

Jiang, S., Chen, W., & Kang, Y. (2021). Correlation Evaluation of Pilots' Situation Awareness in Bridge Simulations via Eye-Tracking Technology. Computational Intelligence and Neuroscience, 2021, e7122437. <https://doi.org/10.1155/2021/7122437>

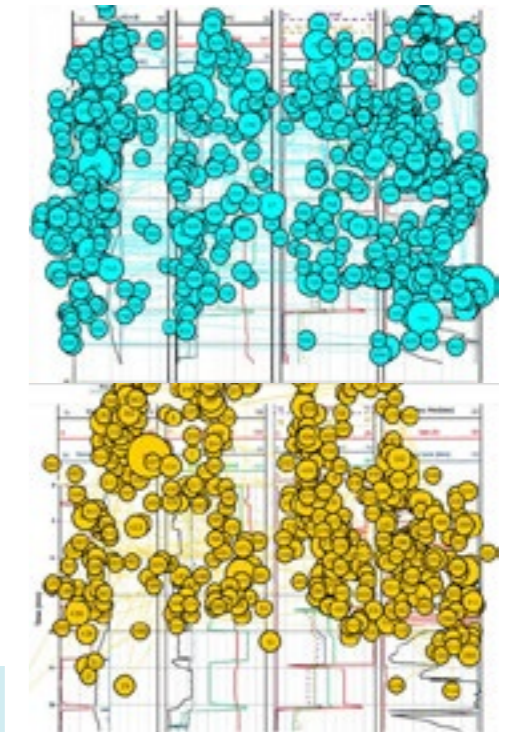
How do experts study situational awareness?

Improving safety during offshore drilling operations by measuring situational awareness

The study explores eye movement characteristics to differentiate the situational awareness between industry experts and novices in a drilling simulation. Participants monitored a virtual reality drilling simulator on a screen and were tasked to interpret the data, explain their understanding, and point out any abnormalities they could observe. Eye movements were captured using a Tobii Pro TX300 eye tracker. The expert correctly identified and confirmed the anomaly, whereas the novice had minimal eye fixations on the anomaly and did not confirm it, as evidenced by the eye tracking data. Hence, oculomotor differences between the expert and novice indicate that an eye tracking system can capture workers' distractions or pinpoint when a lack of situational awareness occurs. A potential use case involves a real-time alarm feedback system that can help during training to make novice participants aware of their deficiencies, which may then improve their performance over time. In summary, eye tracking is an effective and affordable tool to quantify the situational awareness of a drilling operator. In the future, the authors want to use this technology in real drilling operations to make offshore workers safer.



Area of Interests on the dynamically displayed well logging data in Raza et al. (2023) study.



Gaze data distribution of the novice (blue) and expert (yellow) during the full duration of the simulation in Raza et al. (2023) study.

Participants: 24 (novice and experts in industry)

Task: Virtual reality drilling simulator

Eye tracking hardware: Tobii Pro TX300

Key findings: By measuring eye movements, the researchers identified workers' distractions and lack of situational awareness in offshore drilling simulations.

Images were adapted from Raza et al. (2023) under a Creative Commons Attribution License.

Cited publication

Raza MA, Kiran R, Ghazal S, Kang Z, Salehi S, Cokely E, Jeon J. An Eye Tracking Based Framework for Safety Improvement of Offshore Operations. J Eye Mov Res. 2023 Aug 10;16(3):10.16910/jemr.16.3.2. doi: 10.16910/jemr.16.3.2.

Decision-making



What is decision-making?

Decision-making is selecting a course of action among several alternatives (Heekeren et al., 2008). It is a multilayered process that involves information collection from an environment, evaluation, judgment, and consideration of potential outcomes. Real-life decisions vary in complexity and are influenced by personal biases, social factors, and psychological characteristics. **Perceptual decisions** are usually simple and binary, such as whether to stop at the pedestrian crossing. **Value-based (or preferential) decisions** can be more complex and involve multiple sides, such as what to order in a restaurant (Spering, 2022).

People use diverse strategies to make decisions, such as selecting the first option that meets satisfactory criteria or weighing the best vs worst outcome. Despite the inherent complexity of decision-making, it is one of the most crucial cognitive abilities in human factors, given the profound impact that correct and incorrect decisions can have in high-stakes environments.

Why measure decision-making?

- **Predicting human performance.** Measuring decision-making allows us to predict how individuals will perform tasks and make choices in real-world situations, leading to improvements in system design, training, and decision-support tools.
- **Identifying cognitive biases and human errors.** Humans are prone to cognitive biases and errors affecting decision-making accuracy and efficiency. Identify these biases and errors, understand their underlying mechanisms, and develop strategies to mitigate their impact on human performance and safety.
- **Improving system design.** By understanding the cognitive processes involved in decision-making, designers can create interfaces and decision-support tools that are intuitive, informative, and conducive to optimal decision outcomes.

Why measure decision-making with eye tracking?

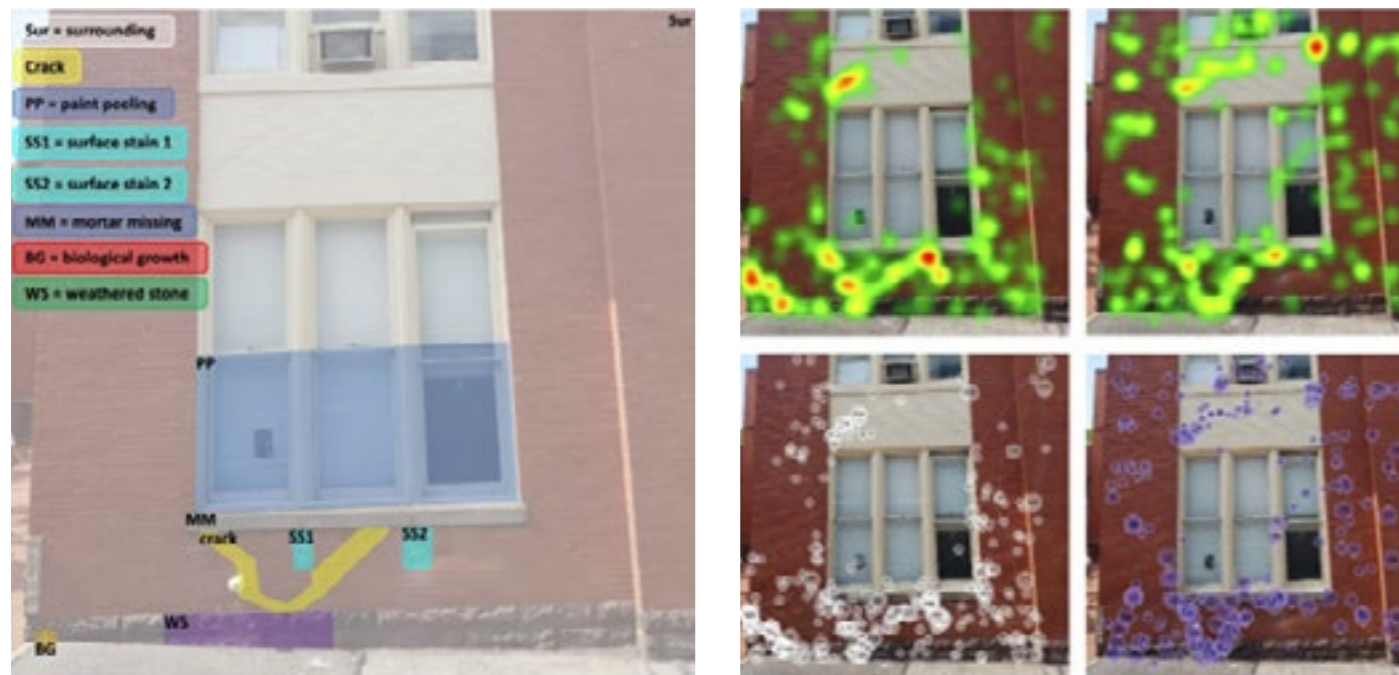
Visual attention is guided by the salience of objects and, not the least, by the individual's goals and expectations (Wedel et al., 2023). This important link makes eye movements a unique window into decision-making processes. With a high temporal and spatial resolution, eye movements allow for the measurement of search and choice behavior in natural contexts. Unlike other methods, such as mouse hovering or questionnaires, eye tracking provides detailed insights into decision-making processes by capturing when and how different decision-making stages unfold.

- **Initial fixations** can indicate the initial interest or automatic attraction to specific options or areas, reflecting the beginning of the decision-making process. Longer fixations on specific items or attributes can indicate deeper cognitive processing or evaluation, suggesting an evaluative decision-making stage (Wedel et al., 2023).
- **Dwell duration** reflects the early processing of alternative options, while the bias in dwell frequency reflects a later stage of evaluations comparing alternatives (Gidlöf et al., 2013).
- **The gaze scan path** can reflect the order in which sensory information is collected and how decision-related evidence is weighted and assimilated with prior knowledge (Gottlieb and Oudeyer, 2018; Spering, 2022). Systematic scanning may reflect a transition from open-ended exploration to targeted search or evaluation (Wedel et al., 2023).
- **Saccade metrics** yield valuable information about the timing of perceptual decisions (Spering, 2022). Long saccades are associated with the search phase, indicating a broader exploration of options, while short saccades typically occur during the evaluation phase, as individuals focus more closely on specific attributes or options (Wedel et al., 2023).
- **Repeated fixations** on the same item or attribute suggest a deeper evaluation or comparison stage as individuals seek to confirm their assessments or choices. Increased fixation counts on specific alternatives indicate consideration and evaluation stages as more attention is given to potential choices (Wedel et al., 2023).
- Approximately 2 to 5 minutes leading to a choice, a visual attention bias toward the item that is finally selected can be observed. This is known as the **Gaze Cascade Effect** (Shimojo et al., 2003).

How do experts study decision-making?

Decision-making in assessing building facade damage

The study investigated the decision-making during facade inspections, focusing on how gaze patterns and eye movements contribute to understanding human interaction with structures. The researchers used Tobii Pro Glasses 3 to record participants' eye movements with architectural engineering backgrounds tasked with inspecting building facades for damage. The study found that areas with longer fixation durations and more frequent visits corresponded to locations where inspectors identified structural damage. This correlation between gaze metrics and damage detection highlighted the role of visual attention in the decision-making processes of facade inspections. Detailed mapping of gaze patterns highlighted areas that attracted more prolonged attention, suggesting a correlation between visual attention and the perceived severity of structural damage. These findings demonstrate the utility of eye tracking technology in understanding and improving decision-making processes during structural inspections, with potential applications in training and developing more advanced inspection technologies.



Different damage areas of interest (AOIs) during visual inspection from Saleem et al. (2023) study.

Heat maps (top) and gaze plots (bottom) of some participants from Saleem et al. (2023) study.

Participants: 11 architectural engineers

Task: A building facade inspection for damage

Eye tracking hardware: Tobii Pro Glasses 3

Eye tracking software: Tobii Pro Lab

Key findings: Eye tracking captured gaze patterns essential for decision-making during a facade damage inspection.

Images were adapted from Saleem et al. (2023) under a Creative Commons Attribution License.

Cited publication:

Saleem, M.R., Mayne, R. and Napolitano, R. Analysis of gaze patterns during facade inspection to understand inspector sense-making processes. Sci Rep 13, 2929 (2023). <https://doi.org/10.1038/s41598-023-29950-w>

How do experts study decision-making?

Pilot's decision-making and visual scanning patterns in low-visibility conditions

The study looked into the effects of flight experience on pilots' decision-making and visual scanning patterns in low-visibility flight conditions. Twenty pilots were split into two groups based on their flight experience. The participants completed flight approaches in a flight simulator in high and low visibility conditions. Visual scanning patterns were recorded with Tobii Pro Glasses 2. Additionally, the mental workload was assessed using eye tracking data. The results showed that, compared to less flight-experienced pilots, experienced pilots were likelier to make go-around decisions in the low-visibility approaches. Furthermore, experienced pilots exhibited a more flexible and adaptable visual scanning pattern by quickly shifting their attention, as evidenced by decreased fixations and increased saccades. These results suggest that combining a visual scanning technique and training method with a slightly weather-focused approach could improve safety in decision-making for inexperienced pilots.



Participants: 20 pilots

Task: Flight in high and low visibility conditions in the flight simulator

Eye tracking hardware: Tobii Pro Glasses 2

Key findings: Eye tracking showed that less flight-experienced pilots would benefit from enlarging their visual scanning span for safer decision-making, especially in low-visibility conditions.

Cited publication:

Shan Gao and Lei Wang (2024): How flight experience impacts pilots' decision-making and visual scanning pattern in low-visibility approaches: preliminary evidence from eye tracking, Ergonomics, DOI: 10.1080/00140139.2023.2298992

Cognitive load

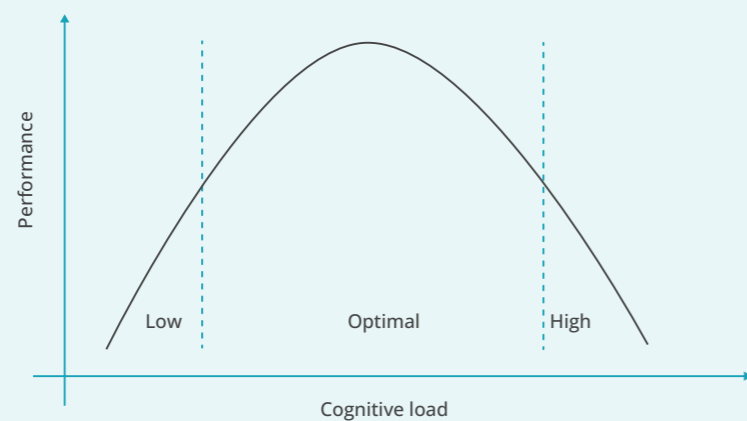


What is cognitive load?

Cognitive load is the amount of mental resources or demands imposed by a task (Orru and Logo, 2019). According to the cognitive load theory, cognitive capacity in working memory is limited, so if a task requires too much capacity, its execution can be hindered (de Jong, 2010). High cognitive load is associated with a subjective feeling of intensified mental activity, effort, stress, or mental fatigue.

Why measure cognitive load?

A direct, inverted-U relationship ties cognitive load and task performance (Biondi et al., 2020). Low or high workload results in dropped performance, while optimal task execution is achieved at moderate workload levels. Maintaining optimal cognitive load is critical for the safety and efficiency of a task execution.



Inverted-U model of cognitive load and performance. The graph illustrates the relationship between cognitive load and task performance. On the left side, a section represents cognitive underload, characterized by passive fatigue and drowsiness. In the middle, an ideal cognitive load is linked to improved performance. Conversely, the right side shows overload, which induces active fatigue and stress and decreases task performance.

High cognitive load

Cognitive overload occurs when the amount of information or stimuli exceeds the cognitive capacity to process it effectively. This results in active fatigue, increased stress, and decreased task performance. Individuals spend more time to process the information while jumping back and forth between different information sources.

High cognitive load results in a higher rate of workplace injuries and accidents (Bonsang and Caroli, 2021).

It leads to slower response times, lower accuracy, and overlooking safety-critical information (F. Biondi et al., 2015; Cummings et al., 2013). Prolonged elevated cognitive load can cause mental fatigue and chronic stress (Mizuno et al., 2011).

Low cognitive load

Cognitive underload arises from monotonous or underloading tasks. It is characterized by passive fatigue and, on some occasions, can manifest as drowsiness and sleepiness (Pan et al., 2023). When not under enough cognitive load, an individual is less attentive and engaged, with low cognitive demand for the task. The individual is not actively processing and engaging with the task or might not be sufficiently challenged by the task.

Cognitive underload can harm performance as much as cognitive overload. Reduced attention due to low cognitive workload can decrease performance, especially in automated systems like flight, driving, and medical or manufacturing automation (Young and Stanton, 2002). Low cognitive load can lead to drowsiness and reduced reaction times. For instance, cognitive underload can lead to vigilance decrements in drivers, reducing their ability to respond to on-road threats (McWilliams and Ward, 2021).

Measuring cognitive loads allows to:

- **Manage workload** and ensure that cognitive demands placed on individuals are matched to their capabilities.
- **Design interfaces** that are intuitive, efficient, and user-friendly. Knowing the cognitive load imposed by design allows to mitigate unnecessary extraneous load.
- **Improve training and skill acquisition** with learning materials optimized for efficiency and effectiveness and minimize cognitive fatigue and time loss.
- **Prevent errors, increase safety** by identifying situations where cognitive overload occurs, and develop interventions to mitigate those risks. Optimal cognitive load enhances performance and promotes safety.

Why measure cognitive load with eye tracking?

Cognitive load can be gauged via self-reporting, error rate, or task completion time. However, these methods are based on retrospective reports and cannot pinpoint the source or exact time when cognitive load occurred. While electroencephalography (EEG) is one of the most established methods for measuring cognitive load in research, its application in real-world settings can be intrusive, requiring expertise for setup and limiting natural movements. Conversely, eye tracking has gained more traction in the past years as a method to measure cognitive load and has yielded positive results.

Blink rate is a significant indicator of cognitive load and has been shown to increase under high cognitive load (Biondi et al., 2023; Valtchanov and Ellard, 2015; Wascher et al., 2016). The validity of blinks as indicators of cognitive load has been measured by matching brain activity during blinks to brain activity, indicating cognitive load (Alyan et al., 2023; Cheng et al., 2023).

Eye Openness signal is a measure of the largest sphere that can fit between the upper and lower eyelids. The eye openness signal is advantageous for measuring blink dynamics beyond basic measures such as rate and duration (Nyström et al., 2024).

Percentage of eye closure over time (**PERCLOS**) is a

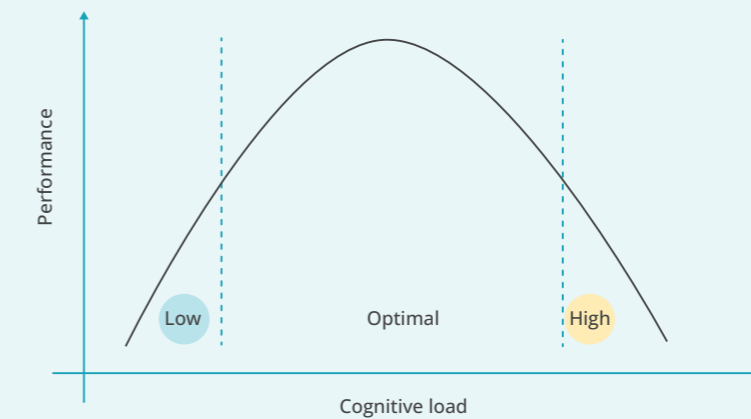
measure used to assess drowsiness or fatigue levels by monitoring the percentage of time a person's eyes are closed over a specific period. PERCLOS is commonly utilized in transportation safety, such as in aviation or driving, to detect when an individual may be at risk of falling asleep or experiencing impaired alertness due to fatigue. Moreover, PERCLOS can classify high and low workloads (Halverson et al., 2012).

Pupillometry is another important metric for assessing cognitive load. Pupil diameter has been shown to accurately infer the high and low levels of cognitive load, where the smaller diameter indicates low levels of cognitive load and larger diameter - overload (Halverson et al., 2012). The relationship between the increase in cognitive load and pupil diameter has been shown in driving (Palinko et al., 2010), education (Borys et al., 2017), aviation (Babu et al., 2019), clinical simulations (Wilbanks et al., 2021).

Eye movements

Fixation duration and saccade length reflect processing demands or cognitive load, with longer and fewer fixations and shorter, fewer saccades correlating with higher cognitive load (Walter and Bex, 2021). While eye movements exhibit variability in predicting cognitive load, they can complement cognitive load assessment in complex tasks, especially when other metrics like PERCLOS or pupil diameter fail to distinguish between fatigue/drowsiness and cognitive overload (Halverson et al., 2012).

An infographic summarizing the types of eye movements that can indicate low and high cognitive loads



Underload

1. Longer fixation duration (Cazzoli et al., 2014)
2. Decrease in saccadic speed (Cazzoli et al., 2014)
3. Small pupil diameter (Halverson et al., 2012)
4. Low blink rate (Halverson et al., 2012)
5. High PERCLOS (Halverson et al., 2012)

Overload

1. Increased velocity of saccadic intrusion – horizontal micro-saccadic movements (Biswas and Prabhakar, 2018)
2. Low number of fixations (Walter and Bex, 2021)
3. Large pupil diameter (Halverson et al., 2012)
4. Decrease in the number and duration of saccades (Walter and Bex, 2021)
5. Higher gaze entropy (Di Stasi et al., 2016)
6. High Blink Rate (F. N. Biondi et al., 2023)

Underload

An individual is less attentive and engaged, with low cognitive demand. The individual is not actively processing and engaging with the task or might not be sufficiently challenged by the task.

Overload

An individual's eye movements are more random and unpredictable. They exhibit signs of scattered attention, trying to manage multiple stimuli or tasks simultaneously. An individual spends more time processing the information while jumping back and forth between different information sources.

How do experts study cognitive load?

Using eye tracking to estimate cognitive load in limb prosthesis users

The study examined whether mobile eye tracking can measure cognitive load during motor tasks. The study participants were prosthetic users and able-bodied controls. Eye tracking data and body movements were recorded with Tobii Pro Glasses 3 while participants performed motor tasks (e.g., level ground walking, stairs up and down, etc.). Participant's target fixation times and pupil diameters were measured and correlated to the subjective rating of cognitive load. The study results showed that target fixation time and pupil diameter correlate with subjective ratings of cognitive load. The study suggests that a mobile eye tracker could estimate cognitive load in prosthesis users during motor tasks, potentially offering a new, objective, practical, and simple assessment method.

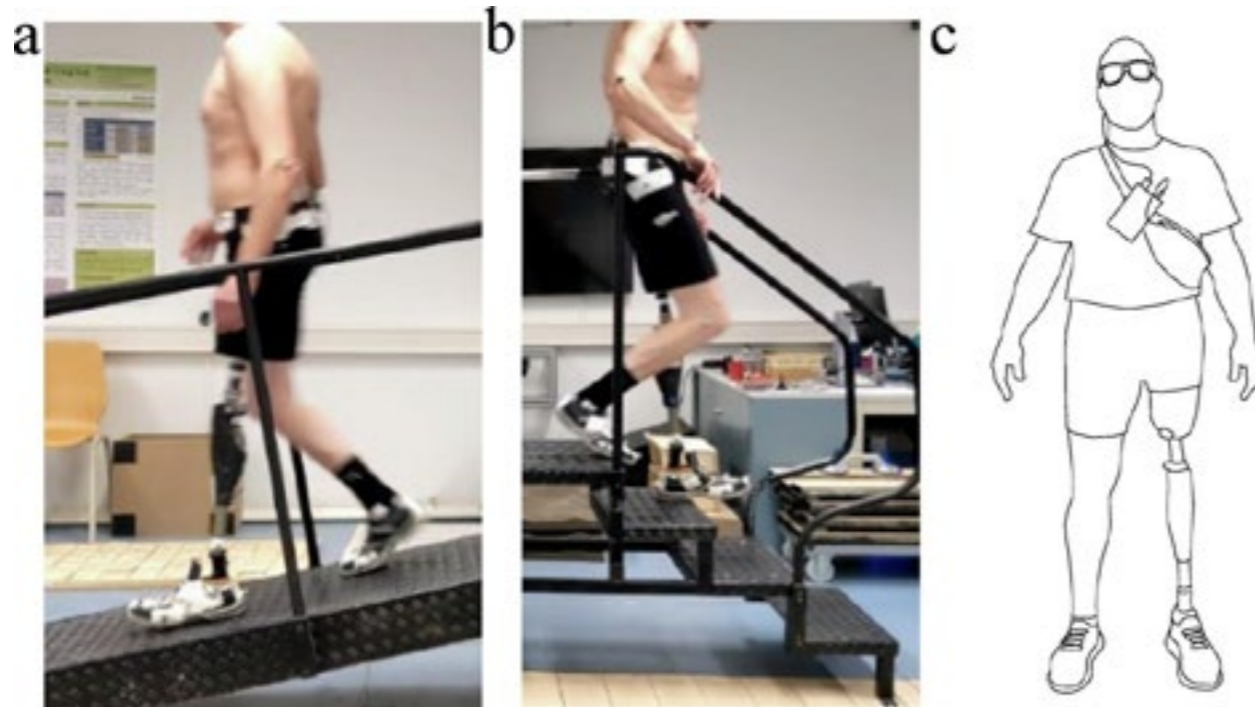


Figure 1 Photos of user testing during ramp descent (a), stair descent (b), and a schematic of a user wearing eye tracking glasses in Manz et al. (2024) study.

Participants: 15 (prosthetic users and able-bodied controls)

Task: Various walking tasks (e.g., ramp descent)

Eye tracking hardware: Tobii Pro Glasses 3

Eye tracking software: Tobii Pro Lab software

Motion capture system: Vicon

Key finding: Eye tracking provides objective cognitive load measures for prosthetic users and can be further developed to assess cognitive load inside and outside the lab.

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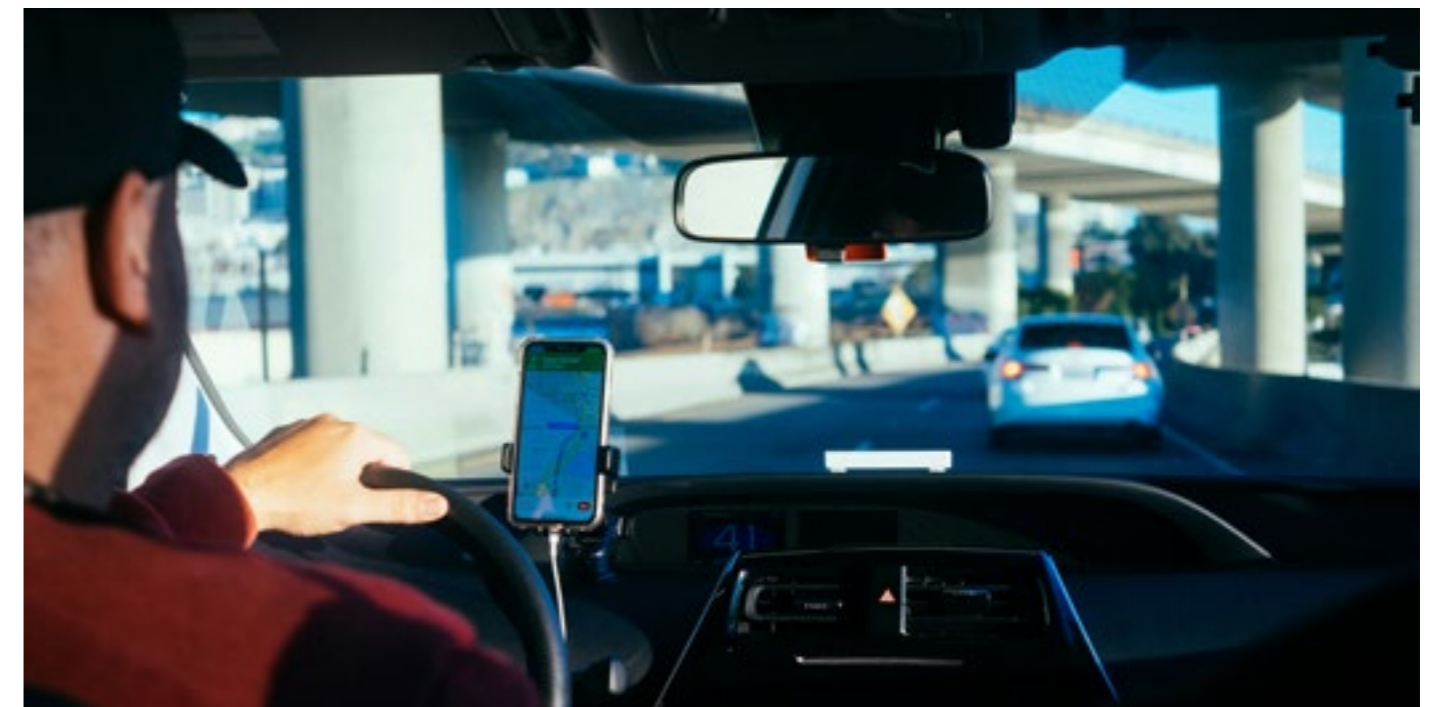
Cited research:

S. Manz, T. Schmalz, M. Ernst, et al., Using mobile eye tracking to measure cognitive load through gaze behavior during walking in lower limb prosthesis users: A preliminary assessment, *Clinical Biomechanics* (2024), <https://doi.org/10.1016/j.clinbiomech.2024.106250>

How do experts study cognitive load?

Exploring sleepiness and fatigue risk of short-haul truck drivers with eye tracking

The research study explored the occupational fatigue risks among short-haul truck drivers, specifically analyzing how sleep patterns, driving tasks, and time-on-task influence driving behavior and eye movement metrics. Eleven professional short-haul truck drivers participated in the study. They underwent a three-day test involving different sleep conditions and two driving tasks (outbound and inbound). Violations of sleep-related legal requirements and insufficient sleep were found to negatively affect drivers' vigilance and driving performance. The interaction between sleep deprivation and the type of driving task exacerbated driver fatigue, indicating that both lack and quality of sleep significantly impact safety. Using eye tracking technology, the study quantified fatigue through metrics such as fixation duration on different areas of interest, pupil diameter, and saccadic velocity. These metrics illustrated how fatigue could impact a driver's ability to concentrate and react to road conditions. The study's conclusions emphasized the need for stricter driving schedule management and sleep patterns among truck drivers to mitigate fatigue-related risks.



Participants: 11 experienced drivers

Task: Outbound and inbound under three different sleep patterns

Eye tracking hardware: Tobii Pro Glasses 2

Key findings: Eye tracking metrics can reliably indicate drivers' fatigue related to lack of sleep on a short-haul drive. The study results inform recommendations for optimizing short-haul truck drivers' schedules and enhancing road safety.

Cited publication:

Zhang, C., Ma, Y., Chen, S., Zhang, J., and Xing, G. (2024). Exploring the occupational fatigue risk of short-haul truck drivers: Effects of sleep pattern, driving task, and time-on-task on driving behavior and eye-motion metrics. *Transportation Research Part F: Traffic Psychology and Behaviour*, 100, 37–56. <https://doi.org/10.1016/j.trf.2023.11.012>

Learning and skill acquisition



What is learning and skill acquisition?

Learning is a fundamental process by which individuals acquire knowledge, skills, and behaviors through experience, study, or instruction. Skill acquisition, conversely, is the process through which individuals learn or develop an ability to perform a task efficiently and effectively. In human factors, learning and skill acquisition directly impact how individuals interact with and perform within various systems and environments. The learning and skill acquisition process undergoes three stages (Fitts and Posner, 1967):

1. **Cognitive.** Individuals focus on understanding the task requirements and developing a mental representation of the skill.
2. **Associative.** During this stage, individuals refine their performance through practice and repetition. The focus is on improving accuracy, consistency, and efficiency by identifying errors, adjusting their approach, and refining their techniques based on feedback and experience.

3. **Autonomous.** In the final stage, individuals achieve a high level of proficiency, and the skill becomes automatic and effortless. They can perform the task with minimal conscious effort, allowing them to focus on higher-level aspects such as strategy, decision-making, and adapting to changing conditions.

Why measure learning and skill acquisition?

Industries' investments in employees' knowledge and skills training are steadily growing; in 2023, it reached over USD101 billion in US-based corporations and education institutions (Freifeld, 2023). With growing expenses on employee training, assessing teaching strategies and learning outcomes not only assures quality and effectiveness but also allows the quantification of investment returns.

- **Understand training program effectiveness.** Organizations need to measure training outcomes to understand their training programs' effectiveness. This

involves determining whether the training is achieving its intended goals and objectives.

- **Determine return on investment (ROI).** Measuring training outcomes helps organizations determine their training programs' return on investment (ROI). This involves assessing whether the benefits gained from the training outweigh the costs incurred.
- **Assess knowledge levels.** Measuring outcomes allows organizations to assess the knowledge levels of trained employees. This helps identify whether employees have gained the necessary knowledge and skills from the training.
- **Identify areas for improvement.** By measuring the knowledge level of trainees after training, organizations can identify areas that need improvement in future training programs. This involves analyzing which sections of the training were practical and which ones need to be enhanced.
- **Monitor employee performance.** Organizations need a reliable procedure to identify any progress made in employees' performance after training. Measuring training outcomes helps evaluate whether there have been improvements in performance as a result of the training provided.

Why measure learning and skill acquisition with eye tracking?

Transfer of expert knowledge and skills. Expert eye movements during a subject-related task performance significantly differ from novice in fields like healthcare (Tien et al., 2014), automotive (Borowsky et al., 2010), aviation (Sarter et al., 2007), offshore operations (Naqvi et al., 2020), computer science (Herman et al., 2021), engineering (Souza et al., 2021).

- Experienced surgeons use more effective gaze strategies than novices, fixating on the most relevant locations and adopting more optimal psychomotor control (Wilson, McGrath, et al., 2010).
- In simulated and live-operating environments, experts and novice surgeons can be differentiated over eye gaze metrics with over 90% accuracy (Richstone et al., 2010).
- Modeling expert gaze strategy helps reduce attention demands when performing complex movements and increases psychomotor efficiency (Wilson, Coleman, et al., 2010).

Reliable and objective skills assessment metric.

Increasing research-based evidence supports eye tracking as an objective assessment of learning and skill acquisition (Tien et al., 2014). Researchers can estimate performance by combining eye tracking data with other measures, such as task completion times or error rates.

Training optimization. Insights gained from eye tracking data can inform the optimization of training programs to enhance learning outcomes. Using eye tracking to evaluate the effectiveness of training assessment has yielded improved outcomes in industrial engineering (Ghanbari et al., 2021), aviation (Lefrançois et al., 2021), and offshore operations (Naqvi et al., 2020).

Real-time feedback: Eye tracking provides real-time feedback on where individuals look while performing tasks. This allows researchers and practitioners to understand visual attention patterns and identify areas of focus during skill acquisition.

How do experts study learning and skill acquisition?

Eye tracking reveals visual strategies in novice and expert surgeons

In the present study, the researchers studied whether observing and replicating the expert surgeon's eye movements in a thoracoscopic surgery video would enhance the learning process of novice surgeons. To address this question, the scientist performed a two-phase eye tracking study. The researchers tracked expert and novice surgeons' eye movements during the first experiment while watching a thoracoscopic dissection video. The study results revealed significant differences in gaze patterns between the two groups while watching the surgical video. While expert doctors focused longer on critical details in the video and paid attention to key anatomical structures, novice doctors tended to deviate their attention from the key regions and spent more time fixating on unrelated areas. In the study's second phase, a new cohort of novice surgeons was divided into two groups to watch the original surgical video (control group) and the same video with the expert's eye movement trajectory attached (experimental group). Post-tests showed that the experimental group better understood the details of the surgical procedure, significantly improving their learning.



Participants: 16 surgeons

Task: Thoracoscopic surgery video

Eye tracking hardware: Tobii Pro Fusion

Eye tracking software: Tobii Pro Lab software

Key findings: Novice and expert surgeons show distinct eye fixation patterns and search strategies during thoracoscopic surgery videos, with novice surgeons benefitting from observing expert eye movement trajectories to enhance their surgical skills acquisition.

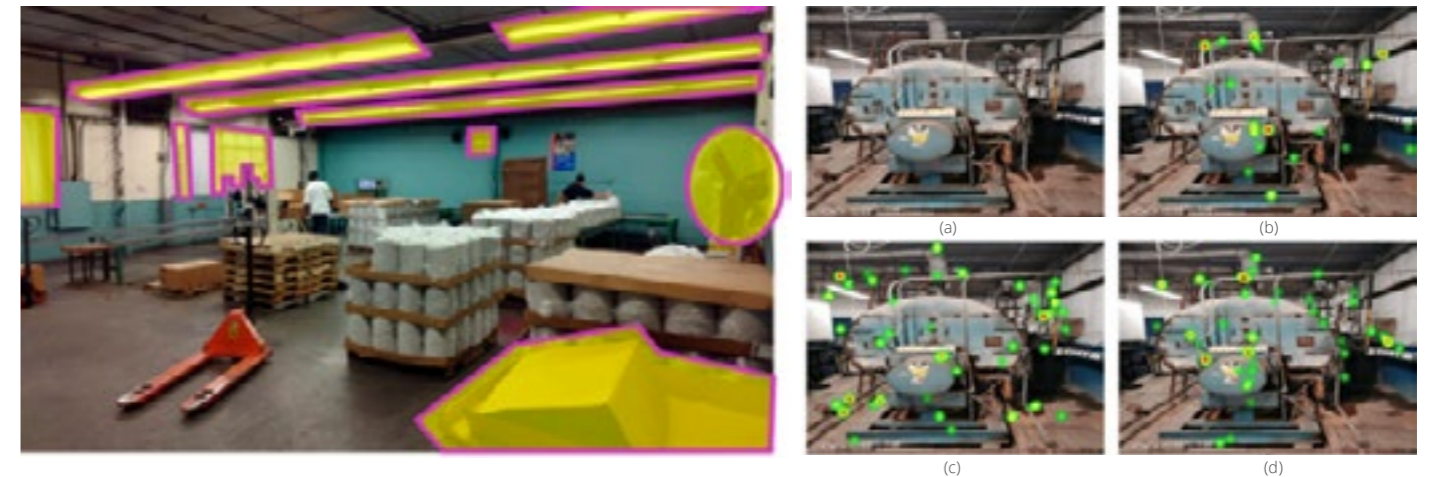
Cited publication:

Ji, Y., Kong, Z., Deng, Y., Chen, J., Liu, Y., & Zhao, L. (2022). The role of eye tracker in teaching video-assisted thoracoscopic surgery: the differences in visual strategies between novice and expert surgeons in thoracoscopic surgery. *Annals of Translational Medicine*, 10(10), 592-592.

How do experts study learning and skill acquisition?

Industrial energy assessment training effectiveness evaluation with eye tracking

The study evaluated the effectiveness of industrial energy assessment training by measuring the attentional allocation of trainees. The participants were tasked with identifying potential energy-saving opportunities from images shown on a monitor while their visual attentional behavior was captured using Tobii Pro Glasses 2. Eye tracking helped in evaluating the effectiveness of the training by quantitatively measuring where participants focused their attention before and after receiving training. The experiment results showed that after receiving the training, the participants significantly improved their performance in identifying energy-saving opportunities, particularly in production recycling and waste management.



Areas of Interest (AOIs) from Ghanbari et al. (2021) study.

Attentional distribution (heat map): (a) original image; (b) participant before receiving the in-class training; (c) participant after receiving the in-class training; (d) experienced participant in Ghanbari et al. (2021) study.

Participants: 16 college students

Task: Answer questions about energy-saving opportunities shown in pictures

Eye tracking hardware: Tobii Pro Glasses 2

Eye tracking software: Tobii Pro Lab software

Key results: The study used eye tracking technology to quantitatively evaluate the effectiveness of industrial energy assessment training, revealing significant improvements in trainees' performance.

Images were adopted from Ghanbari et al. (2021) under a Creative Commons Attribution License.

Cited publication:

Ghanbari L, Wang C, Jeon HW. (2021). Industrial Energy Assessment Training Effectiveness Evaluation: An Eye-Tracking Study. *Sensors*, 21(5):1584. <https://doi.org/10.3390/s21051584>

Team cognition



In industry settings, tasks are often performed in a team rather than by a single individual. It is usually a team of surgeons performing an operation or making an important decision about a diagnosis; two pilots are always present in a cockpit, and construction or manufacturing usually requires a group of people responsible for different parts of the process. Indeed, effective collaboration is crucial for succeeding at complex tasks and harnessing collective intelligence.

Team cognition is the teams' cognitive structures and processes (Cooke et al., 2004). It is a critical contributor to the overall team performance, and the ability to measure team cognition gives a chance to diagnose problems with and implement interventions for team performance.

Evaluating the intricacies of collaboration and group cognitive abilities is challenging due to their multifaceted nature, encompassing cognitive and social dynamics among numerous individuals. Multiple individuals can use mobile eye tracking devices at the same time and provide some valuable insights into group dynamics in real-world settings.

Here are some standard eye tracking metrics that can bring valuable insights from eye tracking in a group setting:

Gaze overlap percentage

The time spent by collaborators focusing on the same area. This metric indicates how much team members focus on the same area simultaneously. High overlap suggests synchronized attention and potentially effective collaboration.

Leader-follower gaze

There is a time delay between a target being referred by one teammate and another teammate fixating on it. Observing the time delay between one team member referencing a target and another subsequently fixating on it can unveil hierarchical gaze patterns and leadership dynamics within the group.



Recurrence quantification analysis (RQA)

Quantifies repeating patterns of dynamic systems by comparing a time series trajectory to itself, exposing underlying temporal dynamics. By analyzing repeating patterns within the team's gaze behavior, RQA provides insights into the underlying temporal dynamics of their interaction, revealing recurring patterns of visual attention and potential coordination strategies.

Cross-recurrence quantification analysis (CRQA)

Measures similarity between two different trajectories. It can reveal gaze coupling and quantify joint visual attention between two time-locked gaze signals. CRQA assesses the similarity between gaze trajectories of different team members, offering a measure of gaze coupling and joint visual attention. This analysis can uncover coordinated attention or shared cognitive processing between team members.

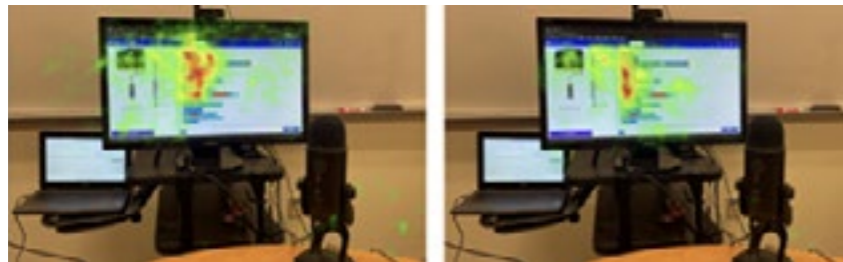
How do experts study group cognition?

Assessment of joint visual attention underlying successful collaboration in a team of programmers

The study investigated the dynamics of gaze patterns during a team collaboration using eye tracking technology. It focuses on the role of Joint Visual Attention and assesses the impact of gaze regularity and gaze coupling on team performance and collaboration quality. The eye tracking data was collected during simultaneous dyadic and triadic teams engaged in a programming task. Findings reveal that team-level gaze regularity, rather than disjointed gaze patterns, significantly improves task performance. Key gaze-based metrics are identified as predictors of subjective collaborative outcomes, suggesting their potential to optimize collaborative success through real-time interventions. This study contributes to understanding visual attention dynamics in team collaborations and highlights the importance of stable gaze patterns in enhancing team performance and collaboration quality.



A triad doing the MakeCode task (left), and a snapshot of the MakeCode task used in Assisted Mapping with the Areas Of Interest (AOIs) highlighted in the Reddy et al. (2023) study.



Heat-maps of a high-performing (left) and a low-performing team depicting their visual attention throughout the task in Reddy et al. (2023) study.

Participants: 44 students

Task: Programming task MakeCode

Eye tracking hardware: 2 or 3 pairs of Tobii Glasses 3 (dyad or triad interaction)

Eye tracking software: Tobii Pro Lab software

Key findings: Eye tracking data revealed the importance of consistent gaze synchronization within teams for effective collaboration and enhanced task performance.

Images were adopted from Reddy et al. (2023) under a Creative Commons Attribution License.

Cited publication:

Reddy, G. S. R., Eloy, L., Dickler, R., Reitman, J. G., Pugh, S. L., Foltz, P. W., Gorman, J. C., Harrison, J. L., and Hirshfield, L. (2023). Synerg-eye-zing: Decoding Nonlinear Gaze Dynamics Underlying Successful Collaborations in Co-located Teams. Proceedings of the 25th International Conference on Multimodal Interaction, 545-554. <https://doi.org/10.1145/3577190.3614104>

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