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Eye tracking — a window to cognitive processes

Abstract

Understanding what humans look at and how that influences cognition and behavior is a fundamental question in psychology and neuroscience. Eye movements are tightly coupled to cognitive processes such as memory, decision-making, and associative learning. Eye tracking combined with behavioral paradigms allow researchers to isolate eye-movement characteristics that reflect the cognitive process of interest and measure them in as controlled a way as possible.

This white paper describes the value of eye tracking in cognitive psychology and neuroscience research. We showcase how eye tracking can be used to study cognitive functions like attention, memory, decision-making, problem-solving, and associative learning. You will also find example laboratory paradigms in which eye tracking can be used to study selected cognitive functions.

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1. Introduction

Every day, people navigate complex visual environments where their retinas are bombarded with an immense amount of visual stimuli. Nevertheless, people can select what stimuli to attend to and which ones to ignore in this highly dynamic process. Humans achieve this selective perception by directing their gaze toward a specific region of the visual scene. Eye movements do not merely reveal the visual information that is being selectively harvested on a moment-to-moment basis; they are tightly coupled to cognitive processes such as memory, decision-making, and associative learning. Understanding what humans look at and how that influences cognition and behavior is one of the most fundamental questions in psychology and neuroscience, making eye tracking a highly suitable technology to address it.

Eye tracking makes it possible to measure various types of eye movements (see glossary), which when placed in the correct context can reveal valuable insights into the mechanisms of cognition. Behavioral paradigms allow researchers to isolate eye-movement characteristics that reflect the cognitive process of interest and measure them in as controlled way as possible. This white paper showcases some laboratory paradigms in which eye tracking can be used to study selected cognitive functions.

This white paper is dedicated to cognitive psychology and neuroscience researchers, or anyone interested in using eye tracking to study cognitive functions like attention, memory, decision-making, problem-solving, or associative learning.

Specifically, in this white paper, you will find:

- The value of eye tracking technology in cognitive psychology and neuroscience research.
- What eye movements can reveal about cognitive processes, including attention, memory, decision-making, problem-solving, and associative learning.
- Laboratory paradigms to study cognitive processes with eye tracking technology.

2. Why use eye tracking to study cognitive processes?

2.1. Eye tracking grants continuous access to cognitive processes

Cognitive processes are interconnected and multilayered, as each undergoes different operational stages over time. For example, consider the sequence of cognitive processes that unfold during decision-making: scene exploration, target detection, and consideration and decision about the response. If, in such a task, we count on an overt behavioral response (e.g., key press, written text, or vocalization), the contributing processes which led to the decision are not captured. Eye tracking data can provide the behavioral end products of the cognitive processes (e.g., decisions) and isolate the different layers of related processes that occur during an experiment.

2.2. Eye movements provide insight into brain function

The brain circuits that support the generation of eye movements have been studied for the past few decades and have resulted in a profound understanding of the relationships between cognition, eye movements, and brain physiology (Hannula et al., 2010; Knudsen, 2018). The rich knowledge of oculomotor circuitry makes eye tracking an excellent method to probe a diverse range of cognitive processes in healthy as well as pathological brain states, throughout a person's life.

2.3. Eye tracking is compatible with other biometric measurements

Eye movement measurements can be combined with brain activity measures and biosensors (e.g., electroencephalography (EEG), electrocardiography (ECG), intracranial EEG (iEEG), galvanic skin response (GSR)), allowing for profound insights into how eye movements, cortical activity, and other physiological variables interplay to contribute to various behaviors.

2.4. Eye tracking allows cross-species comparison and promotes translational studies

Eye tracking and similar or even identical behavioral tests can be performed on different species, for inter-species comparison and uncovering causal relationships between behavior and brain physiology. To date, eye movements measurements have been performed on nonhuman primates (A. M. Ryan et al., 2019), dogs (Karl et al., 2020), mice (van Beest et al., 2021), rats (Wallace et al., 2013), pigeons (Kano et al., 2018), zebrafish (Dehmelt et al., 2018).

3. Attention

Attention is a cognitive process that directs neurocognitive resources toward relevant behavioral goals (Kulke et al., 2016). Recording eye movements is a standard method for measuring where overt attention is allocated. Although the position of the eyes can be decoupled from the location of attentional processing (covert attention), the experience of covert attention is the exception rather than the rule regarding visual processing (Deubel and Schneider, 1996). However, to determine if a viewer is attending to the stimulus they are looking at, the information about attention location can be inferred by measuring microsaccades. The allocation of visual spatial attention is associated with a tendency to make microsaccades toward covertly attended stimulus (Lowet et al., 2018). Measuring microsaccades can inform about the state of attention (overt vs. covert), especially during attentional shifts from one location to another (Yu et al., 2022).

Fixations are brief pauses in eye movements and represent a standard measure in attention research. The general assumption is that the location of the fixation indicates a focus of attention, and the duration of fixations infers the processing efforts toward that spatial location (with exceptions for covert attention) (Holmqvist and Andersson, 2017). Highly salient objects are more frequently selected for fixation, compared to the objects with a low saliency (Nuthmann et al., 2020). Increased fixation duration, compared to the baseline, can indicate difficulties in information processing (Seelig et al., 2021), and repeated fixations to the same visual area can suggest an inefficient search strategy (Rayner, 1998).

Saccades represent rapid eye movements during which visual perception is highly suppressed. Saccadic suppression is crucial for maintaining a consistent visual representation of the world. Although the observer does not process visual information during saccades, these eye movements are still informative metrics for gauging attentional processes. Saccades during visual scene scanning can help infer the timing at which stimulus impinges cognitive processing (Beesley et al., 2019). Our previous experiences influence the way we prioritize visual information processing (e.g., initial saccade location); and so, gaze is more likely to be first directed toward stimuli that have in the past signaled a positive reward (Pearson et al., 2016).

Once people have looked at a specific spatial location, they are unlikely to direct their attention to the exact location again immediately afterward. This phenomenon — inhibition of return — allows people to perform an efficient visual search, as can be experimentally observed in tasks like Visual Search or Posner Spatial Cueing (Posner and Cohen, 1984). This phenomenon illustrates one of many examples of the unique contributions that eye tracking technology has made to further cognitive science development.

3.1. Blinks

Attention fluctuates between being internally and externally oriented, where mind wandering represents the state of attention shifted internally. The two attention states are mutually exclusive — attention to the inner world decreases the capacity to pay attention to the external world, and vice versa (Salvi and Bowden, 2016).

Blinking has been associated with internal thought processing and mind-wandering. Spontaneous blink rate increases following a shift from external to internal processing (Salvi and Bowden, 2016), and less engaging tasks are followed by increased single blink duration and less frequent blinks (Hollander and Huette, 2022).

3.2. Pupillometry

Pupillary constriction and dilation mechanisms are intimately related to distinct brain attentional networks (e.g., locus coeruleus, superior colliculus, and basal forebrain) responsible for alerting, orienting, and executive attention control. These tight physiological links make pupil size an integrated readout of different attention states (read more about pupillometry in attention studies in this comprehensive review by Strauch et al., 2022).

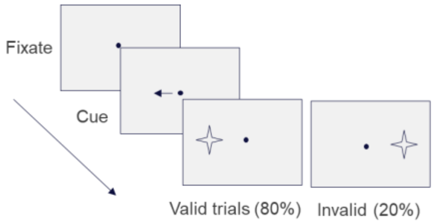
3.3. Attention — behavioral paradigms

Examples of behavioral paradigms in which eye tracking is used to study attention.

Please note: The detailed protocol of a behavior task (e.g., stimulus, stimulus timing, or sequence) will depend on the research question posed. Therefore, we have kept the description of each behavioral task brief and general, providing an overview of the tasks in which eye tracking can be used to study cognitive processes. When planning your research study in detail, we recommend going through the method section of peer-reviewed publications (referred to for every behavioral paradigm). For more detailed examples, please explore our demo projects on Tobii Connect.

3.3.1 Posner spatial cueing task

Study attentional shift, inhibition of return, and orienting of attention.



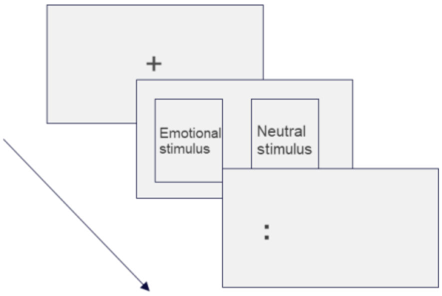
A standard measure is saccade reaction time to target stimuli; microsaccades behavior in predicting the target location.

A participant needs to detect a target stimulus once it appears and respond by making an eye movement toward the target as quickly as possible. Stimulus usually appears on the left or on the right side and is cued just before (as indicated by the arrow). The cues can be valid or invalid. Valid cues are those where the arrow points in the direction followed by the target. An arrow cue points to one side in invalid cues, but the target appears on the opposite direction.

This example was inspired by Kim et al., 2020.

3.3.2 The dot-probe task

Study selective attention and attention bias to emotional stimuli.

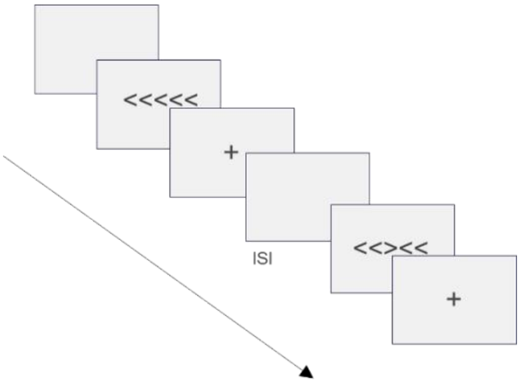


A standard measure is saccade reaction time to target stimuli; microsaccades behavior. In the task, two images are presented simultaneously on the left and right sides (usually with either negative or positive valence vs. neutral images). A participant needs to make a saccade toward the target (the two dots) as quickly and accurately as possible. An attentional bias toward emotional stimuli results in faster reaction times to the target replacing the emotional stimuli compared to the neutral stimuli.

This example was inspired by Mellor and Psouni, 2021.

3.3.3 Eriksen flanker task

Study selective attention and executive control.



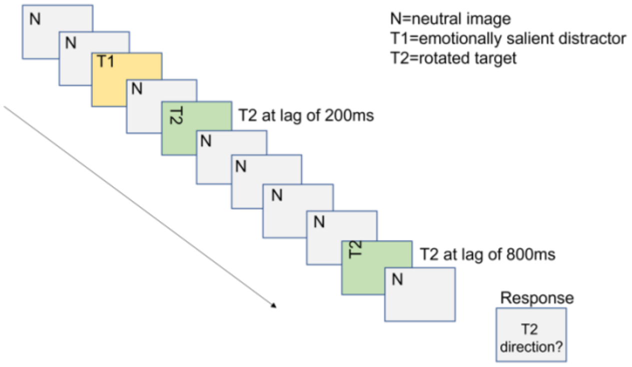
A standard measure is saccade reaction time, but some studies also investigated microsaccade behavior.

Following a fixation cross, either congruent (<<<<) or incongruent (<>><>) stimuli are displayed. A participant responds to the direction of a centrally positioned target arrow as fast and as accurately as possible. A saccade or a button press can make the response. The irrelevant stimuli must be inhibited to respond to a relevant target stimulus.

This example was inspired by Alderman et al., 2015*. One can also use a modified task version Kim* et al., 2020.

3.3.4 Emotional attentional blink task

Study eye movements during emotion-induced attentional blindness, attention dynamics in affective disorders. This example study (Skinner and Ferguson, 2014) measured pupil responses to emotional vs. neutral images.



Emotional attentional blink is a phenomenon in which a brief appearance of an emotionally salient image (T1) (distractor) temporarily impairs attention to the extent that participants cannot detect target (T2) stimuli which were displayed 200-500ms after T1. The trial aim is to report the rotated target (T2) image correctly.

This task also comes in a version without an emotional component — the attention blink paradigm.

This example was inspired by Skinner and Ferguson, 2014

4. Memory

A few key factors guide eye movements in the visual environment: physical characteristics of a stimulus (e.g., color, and luminance), our internal states, and previous knowledge related to visual stimuli (e.g., episodic or semantic memories). We look at objects that are the targets of our voluntary search, but we also dwell on objects that are somewhat novel or contradictory to our knowledge and expectations. Findings from eye tracking studies show that multiple distinct memory representations can be retrieved upon visual scene scanning and compete for preferential oculomotor guidance (Wynn, Ryan, and Moscovitch, 2020). Anatomical and functional links between the oculomotor and memory systems (e.g., the hippocampus, frontal eye fields, dorsolateral prefrontal cortex) (Shen et al., 2016) further support the significance of eye movements in the memory processes. As we will illustrate further, eye movements are functionally relevant for memory encoding and retrieval.

During the encoding phase, free viewing behavior predicts the quality of a subsequent memory (Bylinskii et al., 2015; Damiano and Walther, 2019). For example, incidental memory is better for an object which is viewed longer and with multiple fixations, compared to objects in the same scene which are viewed shorter and with less fixations (Bylinskii et al., 2015; Olejarczyk et al., 2014). Eye movements supply memory with visual input and organize visual inputs in time and space, acting as a memory-binding mechanism (Nikolaev et al., 2022; J. D. Ryan and Shen, 2020). Upon visual information sampling, a scan path sequence is stored together with that visual input to facilitate memory retrieval by comparing new input with stored memory traces (Johansson et al., 2022; Wynn et al., 2019).

During visual information retrieval, people tend to look at previously associated but empty locations, the so-called “Looking at nothing” effect. The fixation of the gaze toward nothing (i.e., blank spaces) reflects the shift from externally to internally oriented attention to retrieve the stored memory representations (Scholz et al., 2018). During “looking at nothing,” previously encoded gaze patterns of a visual stimulus are recapitulated again when retrieving stored memories, referred to as gaze reinstatement. The quality of the recalled memory is predicted by the degree of similarity of the gaze scan path during the memory encoding and retrieval — the more the encoding and retrieval scan paths overlap, the better the quality of the recalled memory (Johansson et al., 2022).

Eye movement patterns can reveal the true relation to the visual stimulus — whether the stimulus is novel or has been seen before. This relationship between the eye movements and the visual stimulus holds irrespective of the intention to conceal this information or even when there is a lack of conscious awareness about the memory (Hannula et al., 2017; Schwedes and Wentura, 2016).

4.1. Pupillometry

Changes in pupil size are shown to be related to memory strength (Otero et al., 2011), recognition of novel versus old objects (Naber et al., 2013), and help differentiate memory identification process in recognition performance (Pajkossy et al., 2020).

4.2. Blinks

Spontaneous blink rate provides valuable insights into changes in working memory demands — increased spontaneous blinking rate reflects the process of updating working memory content and manipulating working memory content (Rac-Lubashevsky et al., 2017).

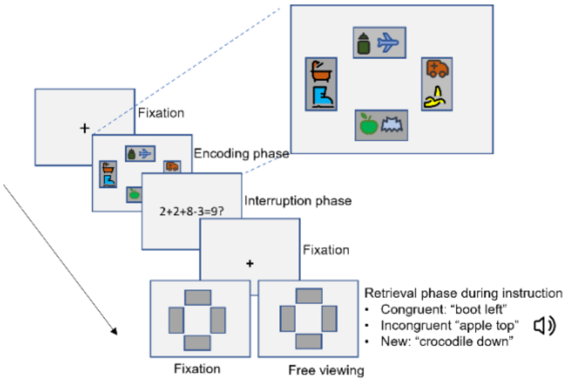
4.3. Memory — behavioral paradigms

Examples of behavioral paradigms in which eye tracking is used to study memory

Please note: The detailed protocol of a behavior task (e.g., stimulus, stimulus timing, or sequence) will depend on the research question posed. Therefore, we have kept the description of each behavioral task brief and general, providing an overview of the tasks in which eye tracking can be used to study cognitive processes. When planning your research study in detail, we recommend going through the method section of peer-reviewed publications (referred to for every behavioral paradigm). For more detailed examples, please explore our demo projects on Tobii Connect.

4.3.1 Visual memory retrieval task

Study the looking-at-nothing effect during memory retrieval.

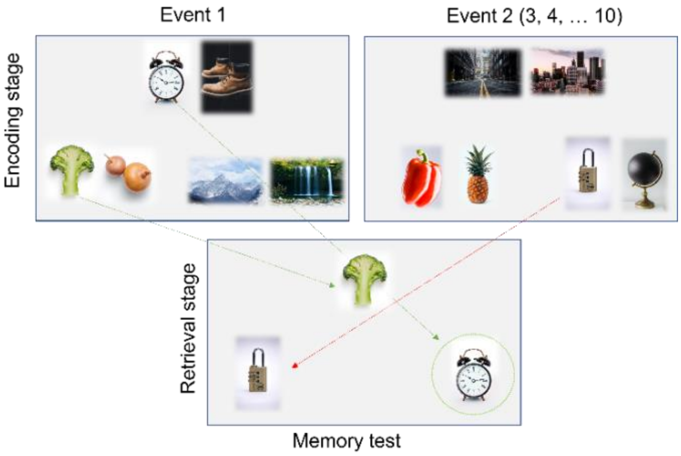


The task consists of three modules — encoding, interruption, and retrieval. During the encoding phase, participants view and memorize eight images and their locations. Then interruption phase follows, during which a simple arithmetic equation appears on the screen. A participant has to reply (by a button press) whether the equation is correct. After a brief fixation, eight blank squares appear at the exact location as previously shown in the images. Participant's task is to judge whether an auditory, verbal location statement (e.g., boot left) is congruent (i.e., the boot was shown on the left) or incongruent (i.e., the butterfly was shown in another location) by pressing an assigned "yes" or "no" button. In one-third of trials, a new object that was not part of the images shown in the encoding phase is introduced. These have to be correctly identified by pressing the assigned key for "new." Different auditory feedback follows each participant's response.

Typical measures include saccades, microsaccades behavior, and their temporal dynamics during the free viewing period, the proportion of gaze dwell time at the critical AOI during this period, and the amplitude of saccades toward the critical AOI. This example was inspired by Kinjo et al., 2020.

4.3.2 Associative memory task

Study eye movements involved in memory formation in an associative memory task.



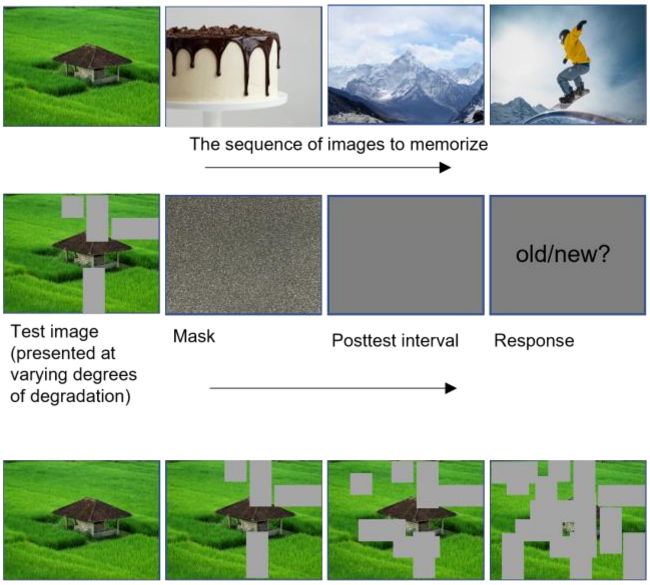
A typical measure is fixations and saccades during the encoding and retrieval phases (read more in the example study indicated below).

The task consists of encoding and retrieval stages. During the encoding stage, two image pairs from three categories appear (e.g., food, place, objects) ten times (referred to as events). In the retrieval stage (test), a cue image is presented at the top, with two images at the bottom representing a different category than the cue image. A participant has to identify which of the two bottom images had appeared together with the cue image in the previously visualized events (i.e., if the broccoli appears as a cue, the correct response is the clock since the two had appeared together in the event nr.1).

This example was inspired by Nikolaev et al., 2022.

4.3.3 Partial-cue recognition memory task

Study the gaze patterns in memory encoding, pattern completion, retrieval, and gaze reinstatement.



A hypothetical example of images presented during the test at different levels of degradation.

A participant views and memorizes a set of 30 images. During the memory test, each image will be presented either in total (0% degradation) or with 20%, 40%, 60%, or 80% degradation (see the example). In the post-test interval, participants are presented with a gray square of the same size as the test images, during which they are instructed to visualize the image presented during the memory test. Afterward, participants have 3s to respond to whether the test image was old or new via a key press. The participant replies “old” only when the test image is the same as an image presented during the study and responds “new” to all other images (i.e., lures).

This example was inspired by Wynn, Ryan, and Buchsbaum, 2020.

5. Decision-making

Eye movements provide a broad spectrum of insights into decision-making processes with a fine temporal resolution on how these processes unfold. Eye movement measurements can help indicate how long it takes to reach a decision, the influence of the expected reward on a decision, or self-confidence about the decision outcome (Spering, 2022). Some specific spatiotemporal characteristics of gaze behavior can inform the decision-making process during all distinct stages — before, during, and immediately after the decision.

Before making a decision, eye movements facilitate sensory information accrual from the visual environment — the process that will define what information will be accessible or even dominate the working memory when the decision-making process initiates. The gaze behavior will 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).

Some specific eye movement indices predict the decision's timing and accuracy during the decision-making process. Saccade metrics (e.g., peak velocity, amplitude, vigor, and end-point scatter) can yield valuable information about the timing of perceptual decisions (Spering, 2022). Eye fixation on a moving target — smooth pursuit — can indicate the decision-formation process and even predict its outcome. In baseball or go/no-go sensorimotor decision-making paradigms (Fooken and Spering, 2019), high smooth pursuit velocity correlates with fast decision-making. The decision end point can be inferred from a response-related suppression of saccades and microsaccades, so-called oculomotor freezing, which indicates the response preparation and yields a marker of a temporal expectation of the decision (Abeles et al., 2020).

When making a decision, eye movements can indicate the subjective feeling of confidence. For instance, saccade peak velocity reflects the degree of certainty with which a decision is made, and it has been shown to increase with accrued evidence (i.e., gaining more certainty) (Seideman et al., 2018). Moreover, saccade, pursuit metrics, blinks, and pupil dilation are all intimately linked to dopamine activity, thus, are implicated in reward processing (Hikosaka et al., 2014). For instance, an increase in the speed of saccadic eye movements reflects the expectation of reward, whereas anticipation of effort decreases it (Shadmehr et al., 2019).

5.1. Blinks

Spontaneous blink rate is a non-invasive, indirect marker of striatal dopamine function, with higher spontaneous blink rate correlating with higher dopamine function (Jongkees and Colzato, 2016). This close link between spontaneous blinks and the striatal dopamine system makes blinks a useful metrics for non-invasive studies of dopamine's role in decision-making. Spontaneous blink rates are correlated with decision outcome and stimulus predictability (read more in this comprehensive review by Jongkees and Colzato, 2016). The spontaneous blink rate is suppressed prior to predictable events, suggesting that the blink rate can serve as a measure of temporal expectation (Abeles et al., 2020). Additionally, blinks provide a reliable measure for cognitive processing, marked by the blink suppression just before the manual response in the visual choice task (Wascher et al., 2015).

5.2. Pupillometry

In decision-making processes, changes in pupil size are sensitive to reward value, perceived effort, certainty about the decision, and uncertainty or surprise related to the decision outcome (Ebitz and Moore, 2019; Preuschoff et al., 2011; Wang et al., 2015).

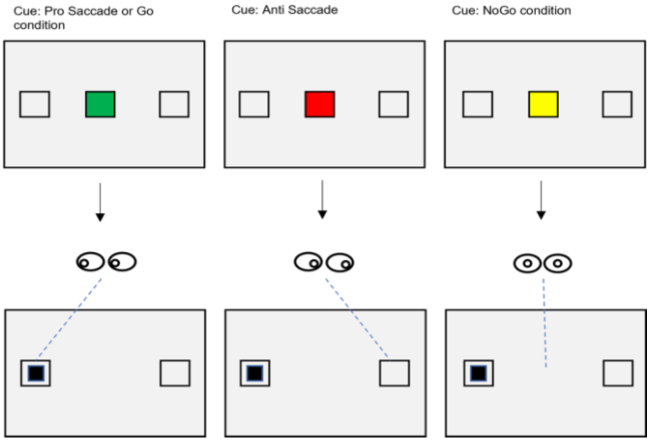
5.3. Decision-making — behavioral paradigms

Examples of behavioral paradigms in which eye tracking is used to study decision-making

Please note: The detailed protocol of a behavior task (e.g., stimulus, stimulus timing, or sequence) will depend on the research question posed Therefore, we have kept the description of each behavioral task brief and general, providing an overview of the tasks in which eye tracking can be used to study various cognitive processes. When planning your research study in detail, we recommend going through the method section of peer-reviewed publications (referred to for every behavioral paradigm). For more detailed examples, please explore our demo projects on Tobii Connect.

5.3.1 Pro-saccade, anti-saccade and go/no-go paradigms

Study decision timing, cognitive flexibility, and inhibitory control.



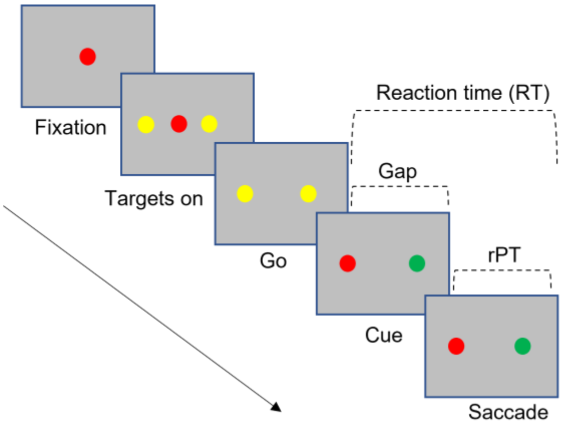
Various saccade metrics are usually used in the analysis (read more in the example study by Opwonya et al., 2022).

Each trial will begin with the presentation of a fixation point which cues the task green for pro/go and red for anti-saccade trials — followed by the presentation of a square target stimulus. Yellow for no-go conditions. For pro-saccade trials, participants are instructed to look toward the target. On anti-saccade blocks, participants are instructed to look at the opposite side of the screen to the target. In no-go trials, participants have to inhibit saccadic response and remain still.

This example was inspired by Opwonya et al., 2022.

5.3.2 Urgent saccadic choice task

Study the interaction between perceptual and oculomotor systems.



The trial starts by fixating on the screen where the eventual target color is indicated (e.g., red). Potential target locations are then indicated during the "Target on." On "Go," a participant can move their eyes between the two locations indicated by yellow dots in this example. After a variable gap, the time indicated by "Gap," a target and a distractor is revealed. A participant now has to make a saccade toward the target stimulus (i.e., red dot). Reaction time (RT) is assessed between the onset of the signal and the onset of the saccadic response. Raw processing time (rPT) is measured between cue onset and saccade onset.

This example was inspired by Seideman et al., 2018.

6. Problem-solving and creativity

Problem-solving involves constructing mental models that depict relevant information and finding the most appropriate solution to a problem. It is a multilayered cognitive process requiring several cognitive functions working simultaneously, such as attention, memory, and creativity (i.e., divergent thinking).

Eye movements can reveal active cognitive representations and how they are manipulated in the mind when involved in problem-solving. When solving problems or thinking creatively, people tend to shift their gaze away from a relevant stimulus and focus on a blank space. The time spent looking away from a stimulus increases with the difficulty of a problem, as attention tends to shift internally, and the looking-at-nothing phenomenon is observed (Ferreira et al., 2008). When viewing blank spaces, eye-movement patterns mirror the mental images used to solve problems internally (Spivey and Geng, 2001). Even during straightforward reasoning activity, such as distinguishing between left and right or above and below, people move their eyes in the respective directions (Demarais and Cohen, 1998). Note how the same looking-at-nothing phenomena and related eye movements can infer different cognitive processes (memory retrieval, problem-solving, or creative thinking) depending on the task at hand.

Successful problem-solving can be identified solely from eye movements. Knoblich and colleagues (Knoblich et al., 2001) demonstrated that fixation on the relevant object for solving the problem increases over time, especially immediately before reaching the solution. The study demonstrated the unique utility of eye tracking during a problem-solving task, which previously counted on traditional performance measures, like solution time and rate measured by a key press or mouse tracking (Knoblich et al., 2001).

Specific eye movements and attention shifts can influence how a person thinks and solves problems. Eye movements guided by attentional shifts trigger a perceptual simulation of an insightful solution. In Duncker's tumor-laser radiation problem (see the paradigm description below), participants who were directed to follow eye movement patterns that embodied the solution were more successful in finding the correct solution than those who could move their eyes freely (Thomas and Lleras, 2009b). Thus, it was demonstrated that it is not the eye movements *per se* that led to the solution but the shift in attention that accompanies the detection of a solution (Thomas and Lleras, 2009a, 2009b).

6.1. Blinks

Blinking has been associated with the process of problem-solving. A sudden insight into a solution — the aha or eureka phenomenon — is preceded by increased blink rate and fewer fixations as compared to other problem-solving stages (Salvi et al., 2015). Looking-at-nothing increases blinking and has been associated with insight and increased creativity (Salvi and Bowden, 2016). Spontaneous blinks are actively involved in attentional disengagement from the external world, allowing more divergent thinking to occur (Ueda et al., 2016).

6.2. Problem-solving and creativity — behavioral paradigms

Examples of behavioral paradigms in which eye tracking is used to study problem-solving

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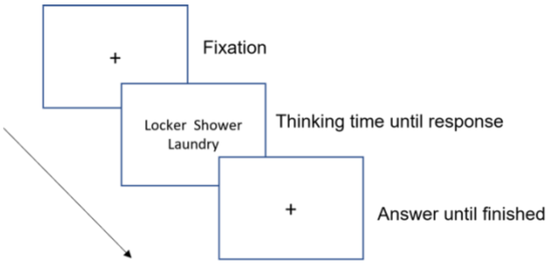
6.2.1 Remote associates test (RAT)

Study eye movements during convergent thinking.

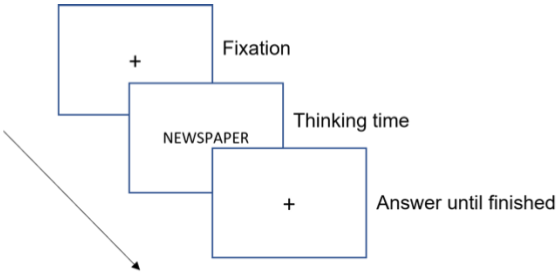


The task is to think of a common word for a three-word set. A participant is told that the common word has various relations with each word. For example, the common word connects each word to become a compound word, or three words imply the same word. After the key press, the participant provides an oral answer. Each trial ends after 60 s (in this specific study example) if participants cannot answer.

This example was inspired by Ueda et al., 2016.

6.2.2 Alternate use test (AUT)

Study eye movements during verbal creativity task

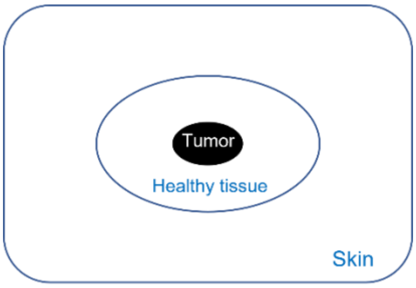


A participant is asked to think of and report all the possible original uses of the presented household item (e.g., newspaper).

This example was inspired by Ueda et al., 2016.

6.2.3 Duncker's radiation problem

Study eye movements during analogical problem-solving.



A participant is given the following task: "Given a human being with an inoperable stomach tumor and lasers that destroy organic tissue at sufficient intensity, how can one cure the person with these lasers and simultaneously avoid harming the healthy tissue surrounding the tumor?" (Duncker, 1945).

This example was inspired by the research study of Litchfield and Ball, 2011.

7. Associative learning

Associative learning is the fundamental principle of how mental representation becomes connected in memory and shapes behavior in humans and nonhuman animals. It is a multilayered cognitive skill that requires both attention and working and long-term memory processes to function in concert. Eye movement measurements can help differentiate the cognitive processes that contribute to learning formation and allow tracking of these processes as they unfold.

One of the most well-established associative learning principles is Pavlovian (also known as Classical Conditioning) (Rescorla, 1988). In Pavlovian conditioning, a neutral conditional stimulus (CS), such as a sound or a light, is repeatedly paired with an unconditional stimulus (US) that triggers a reflexive unconditional response (UR), such as salivation or a blink. After several pairings, the CS will elicit a conditional response (CR) — even when it is not paired with the US.

Typically, the evidence of associative learning is inferred by measuring physiological arousal (e.g., skin conductance or heart rate), through a post-experimental questionnaire, verbal report, or button press. Eye tracking used in an aversive Pavlovian conditioning task demonstrated that learning could be inferred from a specific pattern of viewing behavior prior to explicit knowledge about it. Hopkins and colleagues (Hopkins et al., 2015) observed a disproportionate viewing of the CS, before explicit contingency awareness. The transition between implicit and explicit contingency awareness (Hopkins et al., 2015) could not be inferred from conductance response and verbal report measurements taken during. But eye movements can provide a sensitive measure of implicit associative learning.

Studying associative learning has a high translational value since this behavior can be acquired in various nonhuman animals (e.g., mice, rats, pigeons, and primates), which allows for uncovering the neural mechanisms implicated in learning. In Pavlovian conditioning, where cues (CS) predict reward, some individuals will pursue the cue (CS) — so-called sign-trackers or approach the reward, classified as goal-trackers. Eye tracking and pupillometry can help differentiate between sign- and goal-trackers, which has important implications for diagnostics and developing treatments for maladaptive behaviors (e.g., substance addiction) (Garofalo and di Pellegrino, 2015; Lehner et al., 2017; Schad et al., 2020).

7.1. Blinks

Another basic form of associative learning commonly studied in humans is the Eyeblink conditioning paradigm. In the task, the measure of learning is the CS (e.g., sound) eliciting a CR — eyeblink. CR eyeblinks differ from other types of blinks (e.g., reflex, spontaneous, and voluntary) in terms of their kinematics, as typically measured via the magnetic search coil procedure or electromyography (Schade Powers et al., 2010). However, both procedures are rather obtrusive and may not permit complete freedom of movement of the participant. The eye openness signal available in Tobii eye trackers might facilitate the eyeblink conditioning paradigm performance without compromising differentiation of eyelid movements necessary for the study outcomes.

7.2. Pupillometry

Changes in pupil size indicate some types of associative learning, such as fear conditioning. The anticipation of an aversive event has been associated with a larger pupil size than the neutral baseline (Reinhard and Lachnit, 2002). Pupil size increases during a surprising or unexpected outcome in associative learning (Preuschoff et al., 2011). Pupil dilation is a sensitive and reliable index of Pavlovian conditioning, with a clear effect in aversive (e.g., fear) and appetitive conditioning (e.g., food reward) (Finke et al., 2021).

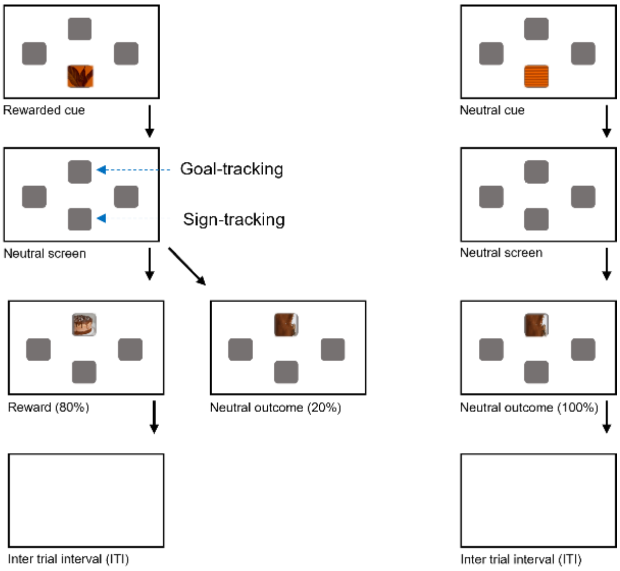
7.3. Associative learning — behavioral paradigms

Examples of behavioral paradigms in which eye tracking is used to study associative learning

Please note: The detailed protocol of a behavior task (e.g., stimulus, stimulus timing, or sequence) will depend on the research question posed. Therefore, we kept the description of each behavioral task brief and general, providing an overview of the tasks in which eye tracking can be used to study cognitive processes. When planning your research study in detail, we recommend going through the method section of peer-reviewed publications (referred to for every behavioral paradigm). For more detailed examples, please explore our demo projects on Tobii Connect.

7.3.1 Pavlovian conditioning task

Study eye movements during goal- and sign-tracking.

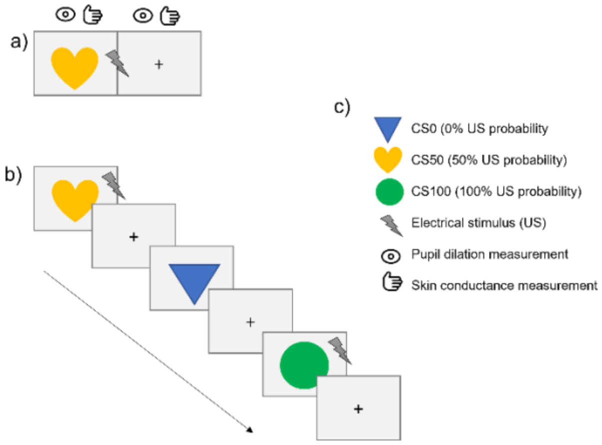


One of the two possible cues (in random order) is displayed on the screen. One cue is associated with a reward (rewarded cue), and the other is associated with a neutral outcome (neutral cue). After the stimulus presentation, a neutral screen is presented to not bias participants toward visible cues. During this time, sign- and goal-tracking are measured. The reward or neutral outcome follows, contingent on the presented cue. The rewarded cue is followed by a reward in 80% of the trials and a neutral outcome in 20% of the trials, whereas the neutral cue is followed by a neutral outcome in 100% of the trials. This conditioned response categorizes participants into sign-trackers (focus on the cue) and goal-trackers (focus on the reward).

This example was inspired by Lehner et al., 2017.

7.3.2 Pavlovian fear-conditioning

Study eye movements during aversive associative learning. In this example study (Stemerding et al., 2022), the researchers measured pupillometry and skin conductance.

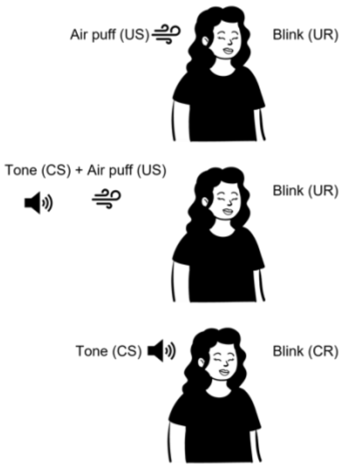


Conditioned stimuli (CS) are three geometrical shapes (square, triangle, hexagon) in different colors presented on the screen. Unconditioned stimulus (US) — a brief electrical stimulus applied to the top of the left wrist — was assigned to each geometrical shape with different probability (0%, 50%, and 100%). The US followed immediately after the CS. The cross in the middle of the screen presents an inter-trial interval.

a) an example trial in which pupillometry and skin conductance measurements could be performed. b) trial sequence. c) figure legend.

This example was inspired by Stemerding et al., 2022.

7.3.3 Eyeblink conditioning



Air puff (US) directed toward human's eye evokes a reflexive eyeblink (UR). The conditioning involves the paired presentation of a tone stimulus (CS) with air puff (US) stimulus. Tone stimulus precedes the air puff stimulus but the two coterminate together. Following repeated CS+US presentation, a conditioned eyeblink (CR) develops in response to the tone stimulus alone. Read more about the task here (Parker et al., 2012).

The eyeblink conditioning paradigm is typically performed with a magnetic search coil or electromyography — rather obtrusive methods that do not permit completely natural eyelid kinematics. Eye openness signal (read more https://www.tobii.com/blog/eye-openness) might benefit the eyeblink conditioning paradigm by allowing free head movement and, at the same time, without compromising the differentiation of types of eyelid movements necessary for the study outcomes (CS blink vs. reflex, voluntary and spontaneous blinks).

This example was inspired by Niehorster et al., 2022 study that performed a similar task, but instead of blinking, they measured the conditioning effect on pupil size (Niehorster et al., 2022).

Appendix A — glossary

Overt attention	Attention shift accompanied by eye movements (Anton-Erxleben and Carrasco, 2013).
Covert attention	Attention shifts to the periphery of the visual field without eye movement (Anton-Erxleben and Carrasco, 2013).
Fixations	A period during which eyes essentially stop scanning a visual scene and remain more or less still. Fixations allow holding a stationary object of interest on the fovea for a detailed visual information intake.
Microsaccades	A small, fast, jerk-like eye movement that occurs during a voluntary fixation, typically less than 1°.
Saccades	Rapid, ballistic eye movements that align a person's eyes toward a new visual location. Occurs in between fixations.
Smooth pursuit	A tracking eye movement used to maintain a moving object of interest on the fovea.
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.

Appendix B — attention studies with Tobii eye trackers

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Appendix C — memory studies with Tobii eye trackers

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Appendix E — problem-solving studies with Tobii eye trackers

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Appendix F — associative learning studies with Tobii eye trackers

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