Before your very eyes: the value and limitations of eye tracking in medical education

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CONTEXT Medicine is a highly visual discipline. Physicians from many specialties constantly use visual information in diagnosis and treatment. However, they are often unable to explain how they use this information. Consequently, it is unclear how to train medical students in this visual processing. Eye tracking is a research technique that may offer answers to these open questions, as it enables researchers to investigate such visual processes directly by measuring eye movements. This may help researchers understand the processes that support or hinder a particular learning outcome.

AIM In this article, we clarify the value and limitations of eye tracking for medical education researchers. For example, eye tracking can clarify how experience with medical images mediates diagnostic performance and how students engage with learning materials. Furthermore, eye tracking can also be used directly for training purposes by displaying eye movements of experts in medical images.

CONCLUSIONS Eye movements reflect cognitive processes, but cognitive processes cannot be directly inferred from eye-tracking data. In order to interpret eye-tracking data properly, theoretical models must always be the basis for designing experiments as well as for analysing and interpreting eye-tracking data. The interpretation of eye-tracking data is further supported by sound experimental design and methodological triangulation.

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INTRODUCTION

Medicine is a highly visual discipline. Radiologists, clinical pathologists, ophthalmologists, dermatologists and cardiologists rely on visual information when interpreting radiographs, ECGs, microscope slides or images of the eye or skin. However, visual information is important to all diagnostic reasoning. Surgeons and anaesthesiologists also rely on their ability to process visual input. Medical education research on visual aspects of learning and teaching can provide guidance for optimally training physicians in these aspects.

Visual processes are largely unconscious and unavailable for introspection. Special research techniques are required to investigate visual aspects of learning and performance, because of the difficulties associated with reporting visual behaviour, leading to incomplete or unreliable information.[1] For example, people verbally report only a subset of their eye movements, or even eye movements they did not make.[2] Eye tracking objectively measures the movements of the eyes to see what a person is looking at, for how long, and in what order.[3] In this way we gain deeper insight into visual aspects of learning and performance. So far, medical education has made little use of eye tracking, in contrast with cognitive and educational sciences, where it has become a reliable technique for understanding and facilitating learning over the last few decades.[4,5]

This paper aims to clarify the value and limitations of eye tracking for medical education researchers. We explain what eye tracking does, what the limitations are, and how these can – at least in part – be overcome. We stress that eye tracking should be employed in a theory-driven manner, both for the design and the interpretation of experiments, to yield meaningful information. Furthermore, methodological triangulation can help us interpret eye-movement research in meaningful ways. We illustrate the value and limitations of eye tracking by discussing two of the many research problems in medical education: the development of visual expertise in medicine and the design of instructional material. Finally, we discuss how eye tracking can be applied directly in teaching.

WHAT DOES EYE TRACKING DO?

Eye tracking is a technique for measuring the movements of the eye(s). The resulting data can be visualised (Fig. 1) and statistically analysed. Table 1 provides an overview of the most commonly reported eye movements. Characteristics of these movements (e.g. the duration of a fixation) form the dependent measures in eye-movement research. Eye-tracking technology is growing in popularity as cheap and easy-to-use commercial systems become available. Modern eye trackers capture a video of the eye to determine its movements in relation to a stimulus on a screen (monitor-mounted eye trackers) or in relation to the world around us (mobile eye trackers). Although less common than monitor-mounted eye tracking, mobile eye tracking can be a very valuable tool for medical education. For instance, Koh *et al.*[6] investigated attentional strategies of novice and experienced scrub nurses during actual Caesarean-section surgeries.

The fovea is the part of the eye with the highest acuity, so when we gather information about the world around us, we direct the fovea towards the information we want to take in. Selective attention refers to the allocation of limited processing resources, by selectively concentrating on, and thus employing our fovea to obtain, certain information while ignoring other information.[7] By attending to information, we select it to be further processed, for storage in memory, integration with prior knowledge or further processing or manipulation.[8] Eye movements can thus be considered the brain's way of gathering information from the visual world.[9]

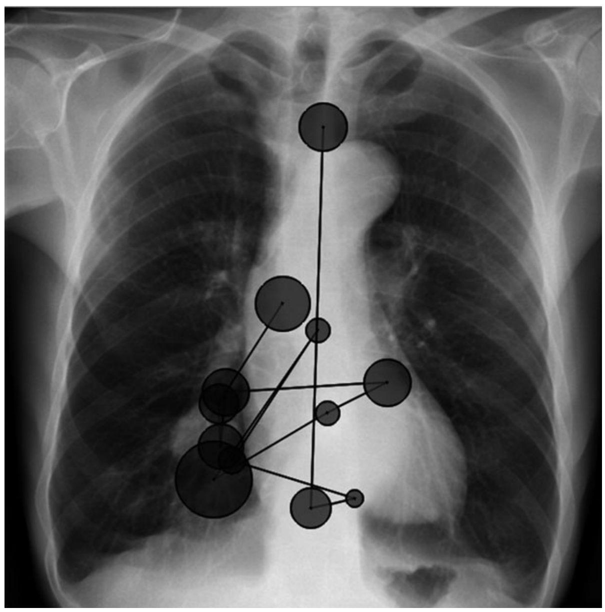

Figure 1 Eye movements of one student studying a chest radiograph. Circles are fixations; the size of the circle represents its duration. The lines between the circles are saccades

Table 1 Eye movements, their definitions and example measures

Eye movement	Definition	Example measures
Fixation	Theoretically, a fixation is defined as the time when the eye takes in information. In practice, a fixation refers to the time the eye is relatively still. This time is similar but not equal to the intake of information	Duration of fixation Number of fixations Dispersion of fixations across a screen
Dwell (also known as gaze or glance)	A dwell is one visit to a relevant part of a stimulus (an 'area of interest'), from entry to exit. A dwell can consist of several fixations	Dwell time Number of dwells
Scanpath	A scanpath is the route of eye movements through space during a certain time span	Scanpath similarity Scanpath length
Saccade	Saccades are the quick movements between fixations, which relocate the focus of attention to a new location. During a saccade we cannot take in visual information	Saccadic amplitude Saccadic duration Saccadic latency Saccadic velocity
Blink	Blinks are moments when the eye is briefly closed	Duration of blink Number of blinks
Smooth pursuit	Smooth pursuit is essentially a slowly moving fixation and enables intake of information. It occurs only with moving stimuli, such as videos, or in the real world	Duration of smooth pursuit Length of smooth pursuit
Pupil dilation	The size of the pupil reflects the activity of the autonomous nervous system and is influenced by cognitive load and emotion	Pupil diameter over time

Many more eye movements exist, such as microsaccades, post-saccadic oscillations and the vestibulo-ocular reflex. These eye movements are predominantly studied in ophthalmology and vision science and less so in applied domains. We refer to Holmqvist *et al.*[3] for a comprehensive overview of eye movements and eye movement measures.

Although the fovea has the highest acuity, it is also possible to take in information from more peripheral parts of the eye. Thus, it is possible to attend to something without actually pointing the fovea at it.[10] This is called peripheral vision and eye tracking is unable to capture this. If the target stimulus is large, monochrome and simple, such as a single letter or shape on a white background, or a distinct movement, it can easily be seen 'from the corner of your eyes'. However, if several letters or shapes are placed around the target (e.g. letters in a text or lung tissue around a tumour), it is impossible to discern the target peripherally[11] and direct or close fixation is required in order to identify the stimulus and perceive the visual details.[12] Peripheral vision, thus, mostly guides visual attention, rather than replacing it.[9] When we spot information from the corner of our eyes that is potentially relevant to look at, we are more likely to move our eyes there, rather than examine it peripherally.[4] Thus, there is generally a close relationship between what the eyes focus on and what the mind is engaged with.[13]

LIMITATIONS OF EYE TRACKING AND HOW TO HANDLE THEM

Because eye movements reflect what the mind is engaged with, eye tracking is a useful tool for research. However, like any research tool, it has clear limitations, and considering these limitations is crucial to understanding what can be inferred from eye-tracking data. An important limitation of eye-tracking methodology is that there is still little knowledge of how cognitive processes can be deduced from eye movements.[14,15] The observed set of eye movements reflects the combined effects of many ongoing (cognitive) processes. For example, what point in a lecture slide a student fixates on may be due to the use of brightly coloured illustrations, the student's motivation to learn from the particular lecture or the human tendency to focus on the middle of a screen (cf.[16]). Although cognitive processes influence eye movements, they cannot be inferred directly from eye movements.

Unfortunately, when presented with eye-movement visualisations or statistics, many people tend to come up with ad hoc explanations for what they see. Take for example a student trying to diagnose a virtual patient in an e-learning environment. One might infer that if the student looks at certain diagnostic information for a long time he or she considers that information relevant for the diagnosis. On the other hand, one could just as easily argue that these eye movements mean the student is having trouble understanding the information. Although ad hoc explanations for eye movements are useful in the brainstorming or piloting phase of an experiment, it should not be forgotten that they are mere ideas, rather than conclusions.

Apart from this very fundamental limitation of eye tracking, several methodological considerations can have an impact on the value of eye tracking for medical education. They are discussed in more detail elsewhere,(e.g. [3]) although we touch on some of them here. Developments in eye-tracking technology eliminate the need to restrict your participants' movements in most cases, making it possible to collect reliable data in the dynamic educational environment. Examples of some commonly used eye-tracking systems can be found in Fig. 2. A quick calibration procedure is required before data collection can start. A calibration procedure typically involves asking a participant to look at specific locations. Based on how well the eye tracker is able to capture the eye for each of these locations, the gaze position for all other locations can be calculated. This procedure does not cause the participants any discomfort and usually takes only a few minutes. However, it may be difficult or impossible to calibrate participants with droopy eyelids, hard contact lenses or narrow glasses, or who are wearing mascara or are of Asian descent,[17] and typically some of the data are of low quality and must therefore be discarded. The experience of the experimenter with calibrating various participants in different experimental settings has a major impact on the quality of the resulting eye-tracking data. High-quality data are required to correctly interpret the results. If the data quality is low, one might think that the student is looking at the clinical information on a virtual

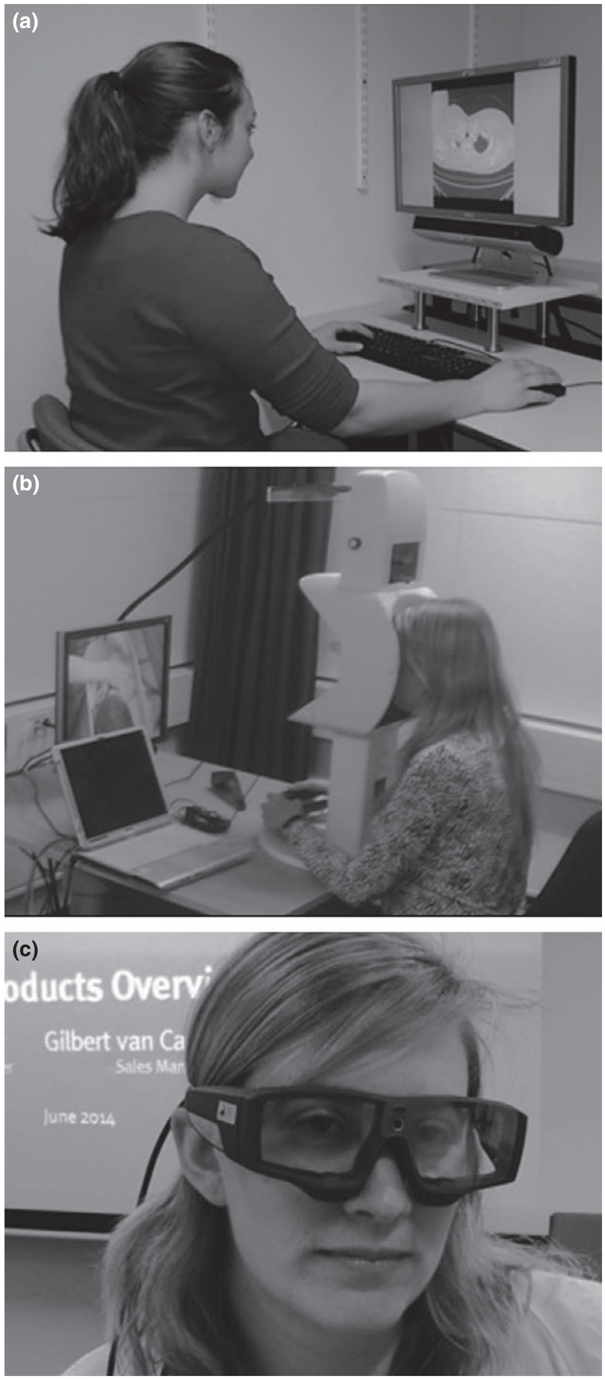

Figure 2 Three types of eye trackers. (a) A monitor-mounted eye tracker. This type of eye tracker is most commonly used for applied research. The participant is requested to stay in the same position but her movements do not need to be restricted. This allows the participant to interact with the computer and the data quality is still high. (b) A tower-mounted eye tracker. The participants head is restricted using a headrest. This type of eye tracker is not commonly used for data collection in applied settings. It is used in basic vision research because it provides a very high temporal resolution. A disadvantage of a tower-mounted eye tracker is that participants cannot use a mouse or keyboard. Furthermore, it is harder to collect think-aloud data during eye tracking. (c) A mobile eye tracker. The glasses are connected to a smartphone-sized recording unit that can be carried in a pocket. This allows for data collection in real-life settings, such as the operating theatre, or a simulation environment

patient, whereas the student is actually looking at their complaints, listed three lines below.

Because data collection and analysis with eye tracking is a laborious, time-consuming process, the sample sizes are often small, which may limit generalisability. Not only data collection but also data analysis generally tends to be labour intensive. Although many commercial eye trackers provide standard measures such as fixation duration and length of saccades, the eye-movement measures that are predicted by a theory are usually more complex. In these cases, labour-intensive coding procedures or complex computations requiring computer programming must be used, involving expertise that the research team might not have. This is particularly true for dynamic and interactive stimuli (e.g. videos and websites) or mobile eye tracking. Hence, working in multidisciplinary teams (including computer scientists who are capable of programming) and searching for opportunities to develop eye-tracking expertise increase the quality of the eye-tracking research.

If methodological issues are eliminated and high-quality eye-tracking data are used, how might valid inferences be drawn from eye-tracking data? Three elements are key to drawing meaningful conclusions about cognitive processes from eye movements. First, eye-movement research must be theory driven. Second, the experimental design must be sound. Finally, methodological triangulation should often be employed.

First, eye-tracking research must be rooted in theory. Research questions should follow from theories. Subsequently, the theory and research question should inform the experimental design, operationalisation of the dependent variables (i.e. selection of the eye-tracking measures) and their interpretation. Only with this approach can valid inferences be made from eye-tracking data. Of course, a basic understanding of human cognitive architecture (e.g.[18] or any cognitive psychology textbook) is also helpful for eye-tracking research. But not only grand theories are useful for eye-tracking research, smaller theories that clearly predict visual processes can be just as helpful, such as the theories on visual expertise or instructional design discussed below. Eye-tracking data can inform, test and expand these theories.

Embedding eye-tracking research in theory can inform a critical step in experimental design: measure selection. Eye-tracking measures (see Table 1 for a few examples) should match the concept under investigation. At times, a concept may not translate directly into available measures, and answering the research question requires inventing appropriate measures or adapting existing ones. Thus, in high-quality eye-tracking research, authors elaborate on the relationship between the concept being examined and the measure used, and do not confabulate the meaning of eye-tracking findings.

Consider again our student who tries to diagnose a virtual patient. Theories of diagnostic reasoning suggest that less experienced students will have trouble distinguishing relevant from irrelevant information.(e.g. [19]) How can these students be helped? Research in visual expertise shows that ‘percentage of time spent on relevant information’ is a measure that could be useful for investigating this phenomenon. One could therefore investigate how much time more experienced versus less experienced students spend on relevant and irrelevant diagnostic information in the module.

Second, an appropriate experimental task must be selected. In a classic eye-tracking experiment by Yarbus, for example, completely different eye-movement patterns were demonstrated when viewing the same image under different instructions.[20] This study showed the importance of carefully instructing participants before recording their eye movements. Hence, different eye movements are likely to occur if participants are told to simply look at a patient video, rather than to diagnose the patient. The ability to properly interpret eye-movement data will depend largely on whether the tasks and instructions given are appropriate. Furthermore, it depends on meaningful differences between the experimental conditions.

For example, one might hypothesise that a virtual tutor could help a student distinguish between relevant and irrelevant information. To test this hypothesis, two identical versions of the virtual patient e-learning module could be developed, one with a virtual tutor and the other without. If the students aided by the virtual tutor spend a higher percentage of time looking at relevant as opposed to irrelevant information compared with the group without a virtual tutor, this effect can be attributed to the virtual tutor, because all other factors, such as the level of difficulty, have remained constant between the two versions.

Finally, although eye movements can provide information on the point of fixation of participants, it is often interesting to know why they looked there. Verbal data, such as think-aloud data,[1] are most commonly collected together with eye-tracking data to answer this question.(e.g. [19,21,22]) Furthermore, performance data are often a useful addition to eye-tracking data. In the example of the student working with the virtual patient, retrospective thinking aloud can provide information about why the virtual tutor helped the student to find the relevant information. Did the virtual tutor help the student to figure out where to find the information he or she needed or to decide which information was actually relevant and should be collected? Of course, performance data, such as learning scores, will have to be examined in order to establish whether spending more time on relevant information actually increases diagnostic performance.

Thus, eye movements reflect cognitive processes, but the relationship between eye movements and cognitive processes is not necessarily straightforward and eye movements cannot be directly translated into cognitive processes. Furthermore, methodological issues can make eye-tracking research challenging. Theoretical embedding, sound experimental design and methodological triangulation are required in order to interpret eye-tracking data properly. We will now explain this in more detail by discussing applications of eye tracking in research areas of medical education.

EYE TRACKING AS A TOOL TO INVESTIGATE VISUAL EXPERTISE IN MEDICINE

Gaining a clear understanding of why experts are able to quickly and accurately interpret medical images such as radiographs and pathology slides is important, as it may help guide the development of educational interventions. We now discuss one of the many theories about development of visual expertise in medicine: the theory of holistic image perception. Kundel and colleagues[23] hypothesised that experienced radiologists quickly obtain a holistic impression of a medical image and possible image perturbations (abnormalities), after which they carry out a thorough foveal inspection of the abnormalities previously identified. This allows them to rapidly find and diagnose abnormalities. The authors explain that the holistic impression would result in longer initial saccades (i.e. 'jumps' with the eyes). Novices in the field do not have the ability to gain such a holistic impression, and thus employ a serial search-to-find process. Kundel and colleagues investigated their theory using eye tracking. Participants were radiologists with varying levels of expertise who inspected mammograms. Also, the authors collected performance data of all participants in addition to eye-tracking data for purposes of methodological triangulation. The more experienced radiologists were indeed found to have longer initial saccades, providing support for the hypothesis. However, the number of participants in this study was limited ($n = 9$) and further research was required (and performed) to support the holistic model of image perception.

The length of saccades (and several other measurements) has been found to differ between experts and novices across many different visual tasks in medicine,[24] and it is often suggested that eye-movement measurements can be considered direct, objective markers of expertise (e.g. the average saccade length could distinguish an expert from a novice). However, the empirical findings regarding the relationship between the length of saccades and expertise vary, and some studies do not find differences between expertise levels based on saccade length.(e.g. [25]) For some tasks, such as diagnosing lymph node abnormalities on CT images, a longer saccade length is a disadvantage rather than an advantage and experts adapt to the task by making shorter saccades as needed.[26] Thus, making general predictions of differences in expertise using eye-movement measurements without considering the task at hand is too simplistic; eye movements should always be interpreted in relation to the task.

Medical education in visual disciplines such as radiology, pathology, dermatology and cardiology could benefit from a better understanding of how experts develop a holistic impression, and how they adapt their eye movements based on the task. One implication of the holistic model of image perception might be that novices should receive additional guidance on finding abnormalities, to avoid losing time on an ineffective serial search-to-find strategy that could otherwise be spent studying the abnormality.

USE OF EYE TRACKING TO INVESTIGATE AND OPTIMISE INSTRUCTIONAL DESIGN

Eye tracking can also be used to shed light on learning and the processes underlying it, in order to inform the design of instructional material. Although many studies on instructional design concern only the outcome of a learning process (e.g. the grades), eye tracking also provides insight into processes underlying learning. It can provide information on how the learner reached, or failed to reach, the learning outcome because it shows how a learner interacts with instructional materials.

Mayer formulated several influential principles for instructional design in his cognitive theory of multimedia learning.[18] One of these principles is the contiguity principle: learning is more effective when related information (e.g. printed text and pictures) is presented close together, so learners do not have to visually search for information in order to be able to integrate it. Interestingly, Jarodzka *et al.*[27] did not find a positive effect of contiguity in a computer-based testing situation. Eye tracking was used to understand these findings. Participants were better able to perceptually ignore (i.e. not look at) irrelevant information when text and pictures were split from each other, as compared with when they were close together. Thus, eye tracking showed that when part of the information is irrelevant, the prescribed format can actually hamper learning or testing.

The use of eye movements in instructional design research reaffirms an important limitation of eye tracking. It is often impossible to know why people make certain eye movements. Holsanova and colleagues[28] attempted to investigate contiguity by measuring the number of transitions between pieces of information. They point out that a higher number of transitions could either mean that there is an interest in integrating the information, or that integration is difficult and many transitions are required. In this case, because it was not possible to ensure a sound experimental design due to an ecologically valid scenario (reading a newspaper for 20 minutes while waiting for a train) and no methodological triangulation was conducted, the eye-movement measurement could not be conclusively interpreted.

Another application of eye tracking for instructional design research is the use of pupil dilation as a measure of cognitive load (see[29] for more information about cognitive load theory). It has recently been applied in medical education: Szulewski *et al.*[30] showed that pupil dilation was greater when emergency medicine trainees answered difficult clinical questions as compared with easier questions. Pupil dilation, however, is much more sensitive to ambient lighting conditions than it is to cognitive load. Thus, lighting conditions need to be kept constant during data collection, which limits the usefulness of pupil dilation for measuring cognitive load in many real-life situations in medical education.

AN APPLICATION OF EYE TRACKING AS A TOOL FOR TEACHING

Eye tracking is primarily a research tool. However, recent studies have started using eye tracking for teaching. Eye movements of experienced physicians can be shown to students while modelling diagnostic reasoning through thinking aloud. Experts' eye movements can direct the students' attention to the relevant information in the video. These are called 'eye movement modelling examples' (EMME)[31] and could also be used in e-learning scenarios. EMME were used to teach students about the diagnosis of epileptic seizures by having them watch videos of babies suffering from seizures or other behaviours that imitate a seizure.[32] Under the control conditions, participants watched videos of patients while an expert paediatrician verbally explained his diagnostic reasoning. Under the experimental conditions, the eye movements of the teaching paediatrician were also displayed. Students learned more effectively when the expert's eye movements were displayed[32] because their attention was most effectively guided to relevant information. Given that eye trackers are becoming increasingly cheaper (the cheapest is $100), it is highly likely that they will be used in regular educational settings in the near future. Thus, classroom-wide use of eye movements for teaching is currently being investigated in several projects, such as the digital classroom in the Humanities Laboratory of Lund University, Sweden (see http://www.humlab.lu.se/en/facilities/eye-tracking/the-digital-classroom/). Further research is required to better understand the specific circumstances under which this method could be used in medical education and when the eye movements can be easily replaced by, for example, a hand gesture.

CONCLUSIONS

Eye tracking is a technique that demonstrates great potential in medical education research because it provides us with a method for investigating visual aspects of learning and performance in the medical and health professions. Furthermore, eye tracking provides a rich source of data at a very fine timescale.

Eye tracking has the potential to uncover the moment-to-moment processes of learning and effects of instruction, particularly when employed in a theory-driven manner. It also has limitations that need to be considered when reading about or conducting eye-tracking research. First of all, cognitive processes cannot be directly inferred from eye-tracking data. Furthermore, there are several methodological challenges associated with eye tracking, which means eye-tracking researchers should be thoroughly trained before being expected to collect valid and reliable data.

These limitations can be overcome in three important ways. First, eye-tracking research should be rooted in theory (i.e. theoretical concepts should be explicitly translated into concrete eye-tracking measures) and the findings should in turn be used to expand on those theories. The conclusions drawn from the eye-tracking measurements should be appropriate to the measure used (e.g. a fixation on certain information leads to the conclusion that the information has been taken in, not that it is remembered). A sound experimental design is required in order to conduct good eye-tracking research. Finally, methodological triangulation should be used, particularly if the research question aims to answer why people look where they look. If these aspects are attended to, eye tracking can provide a method for investigating visual processes in medical education.

Possible applications of eye tracking in medical education are investigating visual characteristics of medical expertise, using eye tracking as a process measure to investigate how students engage with learning materials, and medical experts playing back their eye movements for students.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Eye movements, their definitions and example measures.

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