Open Universiteit

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View on education

I see; therefore, I learn

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I see; therefore, I learn

Inaugural lecture
spoken out in abbreviated form
at the public acceptance of the office of Professor of

Online Learning and Instructional Design
at the Open Universiteit

on Friday 21 October 2022

by prof. dr. H.M. Jarodzka

Colophon

Printing:	ProefschriftMaken.nl
Cover design:	Vivian Rompelberg, Open Universiteit
Cover painting:	Paweł Jarodzki (1958 – 2021), artist, teacher, father
	Oko na lewo, acrylic on canvas, 2013, private collection
Layout:	Halszka Jarodzka, Open Universiteit
Language editing:	John Arkenbout
ISBN:	978-94-6469-074-3

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INTRODUCTION

Nihil est in intellectu quod non sit prius in sensu, said the saint and philosopher Thomas Aquinas (Aquinas, 1259). With that statement, he argued that everything that is in our mind, we initially absorbed through our senses. Consequently, if we want to understand the human mind, how it is constituted, and how it develops – that is, how we *learn* – we must study how humans take in information. We as humans highly rely on our eyes when taking in information; vision is the most complex, but also the best developed of all our senses and the best studied sensation (pp. 10). Hence, knowing where a person looked at, in which order and what they missed, can provide us with crucial information on learning itself. The best way to capture such visual processes is eye tracking (Holmqvist et al., 2011). Initially, these were ceramic scleral coils, which were painfully attached to the eyes. Later, bizarre machines with bite-bars so that participants could barely move (for more information on the history of eye tracking see Wade & Tatler, 2005). Nowadays, eye trackers are becoming unobtrusive, lightweight, portable and increasingly cheaper thanks to continuous hardware and software development. To that point that they are built as lightweight glasses or small bars plugged into the laptop via a simple USB port; at the same time, providing detailed information on where a person is attending to (pp. 15).

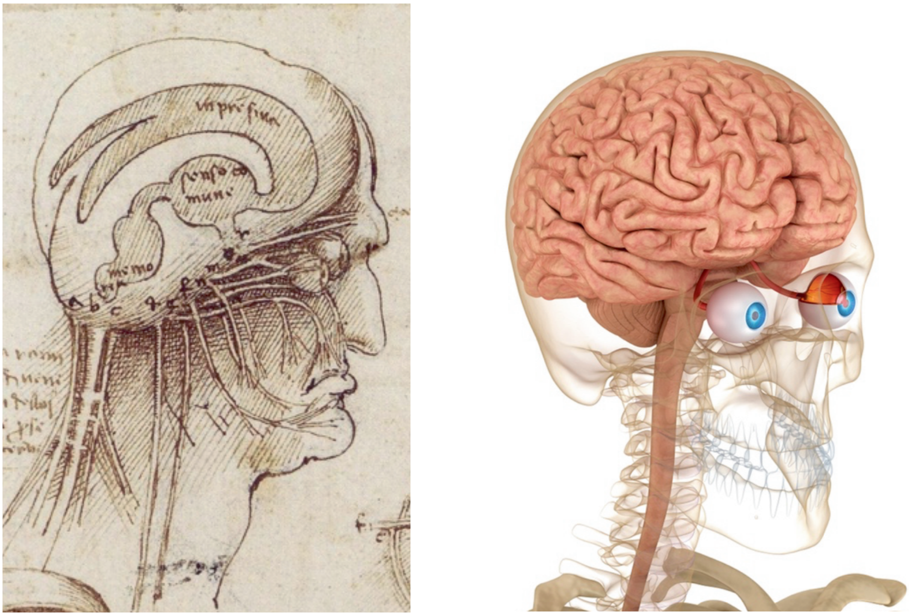
Eye tracking has become such a promising methodology that large tech companies have either purchased eye tracking manufacturers or are developing eye tracking themselves, such as Google, Facebook, Microsoft, or Apple. Hence, it is likely that soon we will see eye trackers built in everyday technological devices and thus entering our everyday life, and ultimately entering our educational systems. It is fruitless to discuss whether this is a good idea or not. Instead, I would like to take the proactive part and challenge researchers to study eye tracking in educational settings to be prepared for this change and be able to provide informed advice to practitioners. But even more important, I would also like to challenge all stakeholders from educational practice – teachers, students, parents, policy makers – to think along with me where this route can bring us, instead of being overwhelmed once this technology is brought upon us by companies. Hence, in my inaugural lecture, I would like to discuss where the chances (pp. 24) and challenges (pp. 55) of this technology lie for our education.

Conveying Knowledge Through Media

Imagine you would have no other knowledge than what you learned from your parents, or what you observed from your peers. This is what our cousins – the other great apes – can do and we probably would not be any further developed than they are. One of our key advantages is that we can not only learn from our closest relatives, but also from others farther away and from those, who have lived long before us. We can do so by taking what we have in our mind – our knowledge, experience, and skills – and transferring this onto something enduring – a *medium*. I hereby follow the definition of the Merriam-Webster dictionary, whereby a medium is "something in the middle position […] conveying something" (Merriam-Webster, n.d.); in the current case, an artefact on which people can encode their inner thoughts for others to decode them again. Think for instance of the different cave paintings made by our Stone Age ancestors: we can see hunting scenes, probably art and religious topics, but also signatures of individuals by imprinting their hands onto the cave walls. Conveying information by externalizing inner thoughts to an artefact can be seen as the first media revolution that allowed us to develop a human culture. Due to an outburst of the population and the accompanying increasing complexity of society, conveying information became more and more difficult and ultimately resulted in developing systematized images, which eventually developed into writing for which early Sumerian scripture or ancient Egypt's hieroglyphs are clear examples of. This can be seen as a second media revolution (for an extended, but comprehensive discussion of these relations, see Harari, 2015). Next to scripture, an important product of externalizing knowledge was the *scientific illustration,* that is a visual depiction of the structure and specific details of a scientific issue (Robin, 1993). Today we can marvel on countless beautiful hand-painted medieval books, contemplate over complex drawings of great minds, such as Leonardo da Vinci's, or admire impressive frescos in churches. What withheld or at least slowed down further development was the extreme amount of time and effort these illustrations required and the simultaneously very limited exposure they had: churches were mostly visited only by those living nearby, while access to books was mostly limited to clergy within a monastery. The next media revolution came to be thanks to Johannes Gutenberg, who introduced book printing thereby accelerating reproduction and enabling media *access* to the broad masses. Books became affordable for larger parts of our society and libraries opened their doors to all citizens and by that democratizing knowledge – if you took the time, you could verify for yourself, whether what elite individuals speaking from stages was true and form your own evidence-based opinion. Our latest media revolution, not only increased access to knowledge even more, but it also enabled mass media *production* – and it is a revolution we all witnessed: the digitalization of our society.

Figure 1

Anatomy of the Human Visual Components According to Leonardo Da Vinci and a Modern 3D Render



The first steps in conveying knowledge via these new, digital media were educational television programs (Fisch et al., 1999). In the past 25 years the internet took over as mass medium with 63% users worldwide and 90% users in developed countries in 2021 (International Telecommunication Union (ITU), 2021). Consequently, the internet has become the key mass medium for conveying knowledge (for more on the chances and challenges of learning from the internet, see Kammerer et al., 2018). One central feature of this digitalization is that producing visual media becomes increasingly easy (e.g., with a couple of clicks you can generate impressive art using the online AI platform Wombo: https://app.wombo.art/). One educational advantage of this development is that the depiction of (scientific) phenomena becomes increasingly authe ntic. As an example, compare the diverse depictions of eyes in Figure 1 to the close-up photography of the eye's retina itself. The disadvantage, however, is that at the same time it becomes far more complex and richer in details and thereby more challenging to process for the human mind (Brucker et al., 2014; Scheiter et al., 2009; Skulmowski et al., 2022).

Our ability to transfer knowledge from our minds to media, from which others, in turn, can learn and benefit, is the driving force of human culture.

This digital media revolution received an additional boost through the past pandemic years when emergency remote teaching across the globe revealed the need to invest and research digital innovations in education (El-Sakran et al., 2022; Iglesias-Pradas et al., 2021; Resch et al., 2022). Consequently, Dutch key organizations for higher education, that is, Universiteiten van Nederland, Vereniging Hogescholen and SURF, signed a declaration to invest in digitalizing their education to improve its quality (Duisenberg et al., 2022; SURF, 2022; Versnellingsplan, 2022a) resulting in a detailed plan of action published this year (J. Kok, 2022). Also, recent national reports emphasize the need to professionalize our teachers and lecturers on digitalized education to become ICT-professionals (Vennix et al., 2021). Even traditionally in-person teaching in laboratories is turning over to hybrid versions (Versnellingsplan, 2022b). This is also in line what Dutch students wish for: a mixture of in-person and online, location-independent education (Huizinga et al., 2022). Obviously, this is not a national Dutch issue, but a worldwide phenomenon with global players (e.g., the UNESCO: https://en.unesco.org/covid19/educationresponse/solutions).

As with the earlier media revolutions, there is no stepping back. Whether you like it or not, our society is increasingly becoming digital. Obviously, this also carries over to our education. I argue that we should not discuss whether to allow these new technologies into our educational settings, as abandoning them would just postpone the problem. Instead, we must discuss *how* and *when* to use them optimally in our education. And to make meaningful statements about this, we must conduct the according research *now.* The main research question that arises now is how we, as educational scientists, can facilitate learning from these increasingly complex and information-rich media. In line with other researchers (e.g., Special Interest Group "online measures of learning processes" from the European Association of Learning and Instruction: www.earli.org/node/50), I argue that in order to facilitate learning – from beginning stages to professional development –, we must truly understand it. And to do so, we cannot only focus on outcomes, but we must study the processes underlying it (for recent developments, see the double-Special Issue by Harteis et al., 2018).

> To truly understand how people learn, it is not sufficient to study its outcomes, but we must zoom in on the way to these outcomes: the processes underlying learning.

The Eye Tracking Methodology

A way to capture visual processes is to track eye movements via specific devices called eye trackers. But what is eye tracking, how does is work and why is it relevant for educational sciences?

Please have a brief look at the picture below (Figure 2: left). Within a few moments, you will get a good first impression of the scenery and you move forward to the next thing – as indicated by the yellow dots and lines. However, what you really took in, are small snapshots that are very detailed, sharp, and colorful, while the rest of the picture is mostly blurry, in grey shades and vague (Figure 2: right). The reason that you have the subjective impression of seeing a full sharp, detailed image in full color is that your mind filled in the rest. Hence, if we want to know what you *really* took in with your eyes, I cannot ask you that simply, but I must measure where your eyes looked at. And this is exactly what eye tracking can do. In the following paragraphs, I invite you to join me in the dive into the psychological, physiological, and technological foundations of eye tracking.

Figure 2

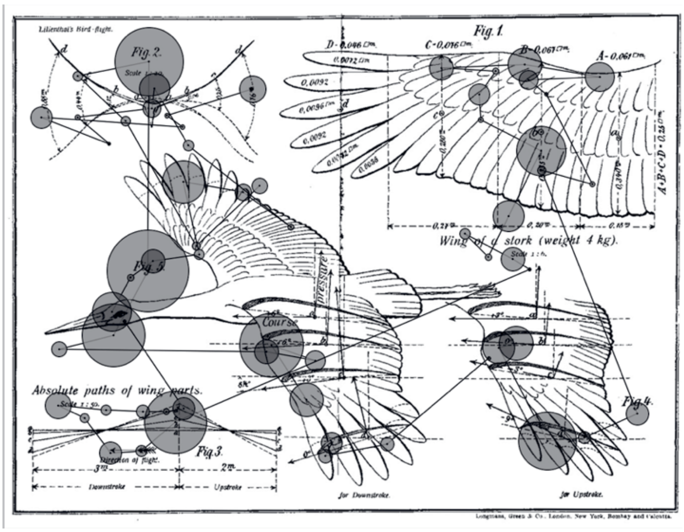
Visually Dense Scene Overlaid with a Visual Scanpath (Left) and Adapted to Depict a Physiologically 'Correct' Perception

The Physiology and Psychology Behind Eye Tracking

Why do we move our eyes at all? Why can we not simply take in the entire scene at once like a camera lens? And when we move our eyes, why do we move them towards specific areas? To answers these questions, let us begin with a brief introduction to human visual perception (for an introduction to this topic, see Spielman et al., 2020; Wolfe et al., 2021).

Figure 3

Depiction of the Flight of Birds by Otto Lillienthal (1889) Overlaid with a Scanpath

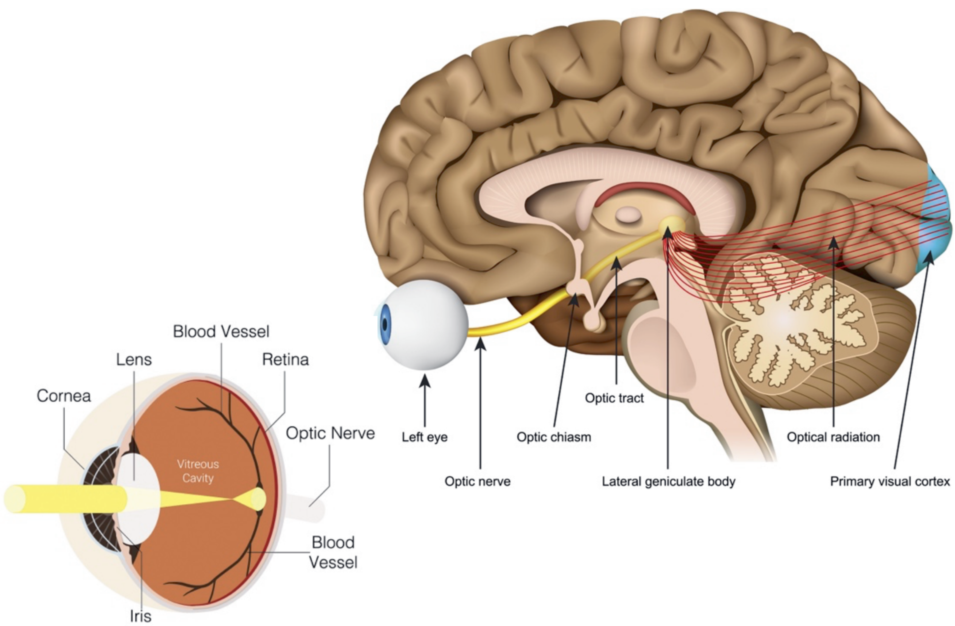


Note. Otto Lilienthal (1848 – August 10, 1896), Public domain, via Wikimedia Commons

What happens when we study a page from a scientific textbook, such as the drawing of birds' flight by Otto Lillienthal (Figure 3)? It all begins with the translation of physical energy, that is light, into psychological sensations, such as seeing a line. This process is called *transduction* (Dowling, 1967; Wald, 1935). First, the light waves reflected from the stimulus (i.e., the drawing) reach the according sensory organ, which is the eye. The light waves enter via the pupil and are projected at the backdrop of the retina, where they activate the receptors. These receptors are called cones and rods which, once activated, lead to neural activity (Figure 4: left). This neural activity is processed in specific areas of the sensory cortex resulting in a specific sensation such as colors, patterns, textures, motions, or depth. *Sensations* are the simulations of neural receptors that result in neural impulses representing the things of the inner or the outer world (Figure 4: right). It is important to note though this does not mean that we have understood how a bird flies nor recognize a bird in this drawing. To do so we need perception. *Perceptions* are richer processes of higher order; they involve interpretations and classifications of sensations (Gibson, 2002; Spielman et al., 2020).

Figure 4

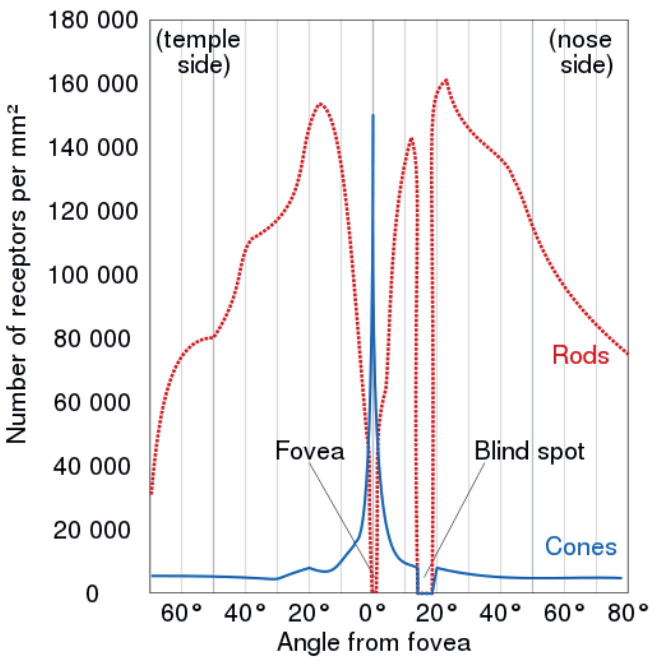
Cross-section of an Eye with the Way of Light Depicted (left) and Cross-section of the Brain with the Visual Pathway Depicted (right)



But why does the eye have to move at all instead of taking in all information in at once (Rayner, 2009)? The reason lies in the function and the distribution of the two receptor types across the retina (Curcio et al., 1990; Wolfe et al., 2021): cones primarily respond to color and detail (most important for daytime vision) and are concentrated in one small region of the retina called *fovea*. Rods on the other hand, respond to variations in luminosity and movement (mainly for nighttime vision) and are mainly distributed in the periphery of the retina (Figure 5). By moving the eyeballs, we can thus relocate which area of the stimulus falls onto the fovea and can thus be sensed in detail. In this way, we can scan the entire drawing to get a good impression of its content (Figure 3). This is the very reason why we move our eyes at all. And this is what eye tracking measures.

Figure 5

Distribution of Optic Receptor Cells – Cones and Rods – Across the Retina



Note. Density of rod (dotted line) and cone (solid line) photoreceptors along a line passing through the fovea and the blind spot of a human eye vs the angle measured from the fovea, based on 'Foundations of Vision' by Brian A. Wandell. Distributed under a CC BY-SA 3.0 license. Retrieved 10:08, May 16, 2022 from https://commons.wikimedia.org/w/index.php?title=File:Human_photoreceptor_distribution.svg&oldid=631700723.

We move our eyes to relocate what information falls onto our fovea so we can perceive it in detailed resolution.

But what determines *how* we scan an image? There are three influences on our scanning behavior operating at the same time. First, ‘bottom-up’ features of the stimulus itself influence where we look at (Itti, 2007; Niebur, 2007; Wolfe & Horowitz, 2004). These are characteristics within the stimulus itself, meaning the way single elements stand out in relation to other elements, called *visual saliency*. Such as a bright color, a sharp edge, a different orientation, or a motion. These features can all be combined to compute their saliency and create a so-called saliency map to predict where an observer would look at in which order (Itti & Koch, 2001; Parkhurst et al., 2002)[1]. Second, the physiology of the eyes, the built-up of their muscles and the set-up of our neurological system result in systematic tendencies in our viewing behavior – irrespective of the stimulus itself. Such as that we tend to look more in the center of a stimulus (Tatler, 2007) and to move our eyes rather in a horizontal than a vertical manner (Foulsham & Kingstone, 2010). We also tend to make several local eye movements, followed by single global eye movements (Tatler & Vincent, 2008). We are likely to return to already inspected elements (i.e., regression), however, only after some time as an ‘inhibition of return’ process prevents us from sticking endlessly to a just inspected element, which in turn keeps our visual inspection of an image ongoing (Cheal & Chastain, 1999; Klein & MacInnes, 1999). If researchers take these aspects additionally into account, they can predict observers’ eye movements even better than based on stimulus features alone (Tatler & Vincent, 2009). Third, the movements of our eyes are also influenced ‘top-down’ (Yarbus, 1967). These are features of the observer themselves, such as a specific task in mind (Einhäuser et al., 2008; Foulsham & Underwood, 2007), expectations about what they see (Fernandes et al., 2021; Torralba et al., 2006), or prior knowledge – or a lack thereof (for more details on this expertise effect see pp. 45). Often, these features turn out to be more influential than the bottom-up features to determine, where an observer looks at

[1] For a rich source on this topic, see: http://ilab.usc.edu/toolkit/downloads.shtml

(Henderson et al., 2007; Underwood et al., 2006). This effect can already appear on a neurological level (Gilbert & Li, 2013; T. Lee, 2002).

The way we move our eyes depends on what we look at (bottom-up features), how we move our eyes (systematic tendencies), and what we are looking for (top-down features).

But looking at something is obviously not the same as *seeing* it. The first being a sensation, the latter the perception. A classical experiment illustrating this is the 'invisible gorilla' (Neisser & Becklen, 1975; Simons & Chabris, 1999): participants were watching a basketball game on video and were asked to count how often one group of players passed the ball. During this game, a person dressed as a gorilla[2] walks through the court – right amid the players – and stays there pounding on the chest for a total of nine seconds. Curiously, most participants did not *see* the gorilla. Later eye tracking experiments showed that participants did *look* at the gorilla, but still did not *see* it (Memmert, 2006) – an effect replicated in advertisement banners (Gelderblom & Menge, 2018) and even in radiologists looking for nodules overlooking a gorilla drawn in lung X-rays (Drew et al., 2013). This phenomenon is referred to as inattentional blindness and describes a mental state of selective attention to specific elements in our surrounding based on their relevance to the task at hand and the neglect of irrelevant elements – even if these are salient. But this is good news as the same is true the other way around: we can filter out relevant information from a magnitude of irrelevant information. This is known as the cocktail party phenomenon, where we can hear someone saying our name within a noisy surrounding (Cherry et al., 1953).

What does this possibility for disentangling between attention and gaze location mean for eye tracking? Essentially, not that much. Most important is that we provide participants with a clear instruction so that they have a task in mind when inspecting a stimulus. Given such a clear instruction, eye tracking researchers agree that what people look at largely corresponds to what they cognitively process (eye-mind-assumption: Just & Carpenter, 1976; Rayner, 2009) – an assumption that has been supported in many studies throughout diverse tasks (e.g., Hayhoe et al., 2003; Land & Hayhoe, 2001; Pelz & Canosa, 2001). Together with Ellen Kok, we took a

[2] In the original experiment this was a person carrying an open umbrella.

more cautious stance by stating that looking at an element is necessary for taking it in, but it is not sufficient; what we need additionally is attention (E. M. Kok & Jarodzka, 2017a, 2017b). But even considering this precaution, eye tracking allows us for drawing conclusions on higher-level processes, such as memory (Foulsham et al., 2012), reading (Rayner, 2009), or other cognitive and metacognitive processes (Van Gog & Jarodzka, 2013). A final note on how to interpret eye tracking is that perception, that is the interpretation of what we look at, is not only something that happens *after* sensation; it is also the *driving force* of where we look for further (Gibson, 2002).

When we look at something, it does not guarantee that we have taken it in; but if we did not look at it, we certainly have not.

The Technology of Eye Tracking

Eye tracking has come a long way since its very beginnings (for a detailed handbook on this methodology, see Holmqvist et al., 2011; for a broader introduction to research methods in multimedia learning, see Jarodzka, 2021; for a historical overview of eye tracking, see Wade & Tatler, 2005). The first studies on eye movements were conducted by the ophthalmologist Louis Emile Javal in the 19th century; he simply observed people while they were reading. By this simple technique he already discovered something very crucial that still holds true, namely that when we read, our eyes do not simply smoothly flow along the lines. But they make quick jumps instead. The jumps are called *saccades* and turned out to be the fastest movements our body is capable of. Thus, during those, re-allocations of our visual attention, we are virtually blind[3] and do not take in new visual information (Matin, 1974; Rayner, 2009). The brief stops in-between these jumps are called *fixations*. And these are the moments we take in information and are thus of utmost interest for the researchers.

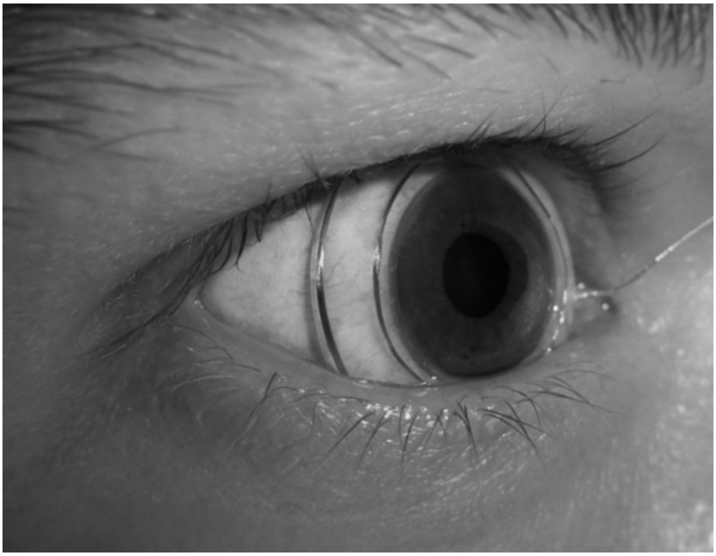
After discovering these two different eye movements and their functions, the next question was thus, how to measure *where* exactly these eye movements fall into. To address this question Edmund Huey developed scleral coils that measure exactly

[3] It is possible to detangle the attention from the fixation location (Posner, 1980). However, this is rather an exception than an inherent function of our processing system according to eye tracking pioneer Keith Rayner (2009)

the movements of the eyeballs. In Figure 6 you see a relatively modern version of such coils. But in their beginnings, these were small cups with a small whole in the center – made out ivory, aluminum, ceramic, or rubber – placed onto the eyeballs to which a wire was attached that moved along with the eye and thus could draw exactly how an eye moved. This pioneering work was brilliant as it could indeed measure the movements of the eyeball very accurately. On the downside, to stand such a torture, the eyes had to be anaesthetized with cocaine. Of course, eye tracking would not be as widely used as it is if it were not for a further development, namely video-based eye tracking. In Figure 7, you see an already well-developed device from the 1960ies that closely films the eyeballs and infers from that how they move. And basically, this is how modern eye trackers still work.

Figure 6

Scleral Coils for Measuring Eye Movements



Note. Scleral coils by Chronos Vision. Adapted from “Haptic Feedback to Gaze Events”, by B. Thankachan, 2018, Faculty of Communication Sciences, University of Tampere, p. 13 (DOI:10.13140/RG.2.2.28643.50729).

Figure 7

Video-based Eye Tracker Used by A.L. Yarbus in 1962.

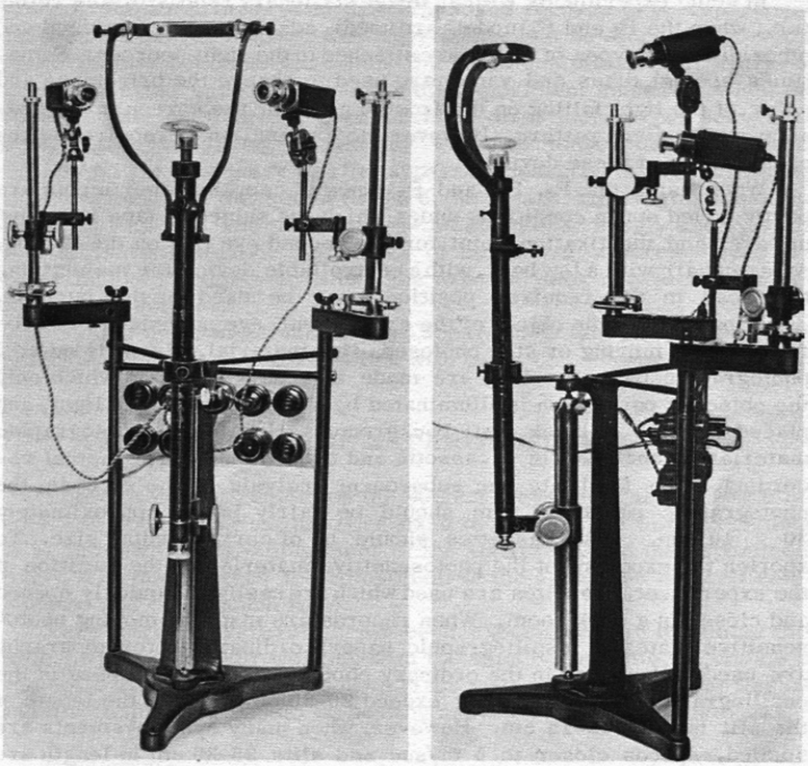


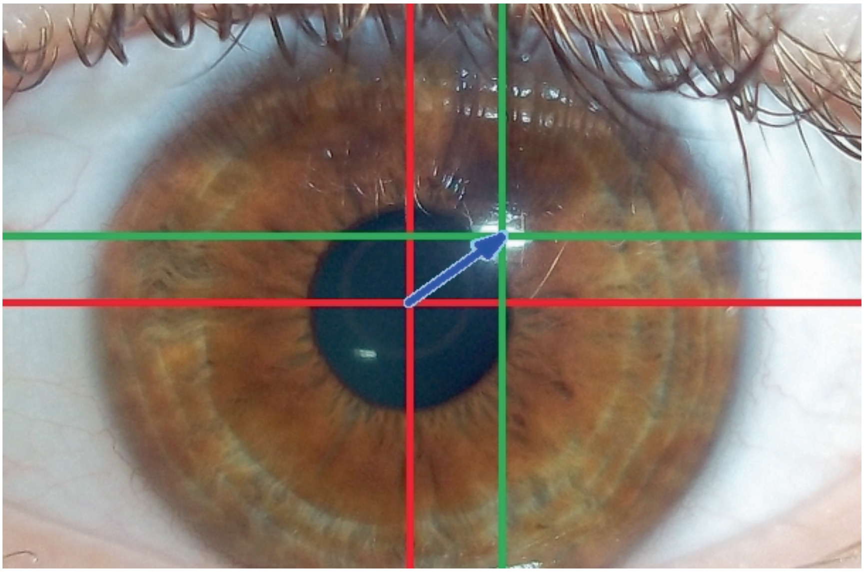
Fig. 21. The apparatus used in recording eye movements.

Note. Yarbus, A. L. Eye Movements and Vision. Plenum. New York. 1967 (Originally published in Russian 1962). Distributed under a CC BY-SA 3.0 license. Retrieved 15:08, September 26, 2022 from https://commons.wikimedia.org/wiki/File:Yarbus_eye_tracker.jpg

Let me briefly explain this video-based methodology (see Figure 8). First, one or several infrared lights are directed towards the eyes. These lights cause reflections on the cornea. Then, an infrared camera captures this image of these eyes. In a next step, an image processing software registers the darkest and the brightest area in the image, which are the pupil and the corneal reflection. When the eyes move, the distance and allocation of these two points changes in relation to each other. Thus, this distance between these two spots in combination with the coordinates of a computer screen – or the room this person is situated in – reveals the exact location of where this person looked at.

Figure 8

The Human Eye as Seen by the Eye Tracking Software



Note. Image created by Björn Markmann. 2015. Distributed under a CC BY 3.0 license. Retrieved 15:13, September 26, 2022 from https://commons.wikimedia.org/wiki/File:Visible_light_eye-tracking_algorithm.jpg

Current Types of Eye Trackers

Nowadays, diverse types of eye trackers are available. Each type comes with its own advantages and disadvantages. *High-resolution* eye trackers have high-quality cameras directed towards the participants' eye(s) and these cameras capture an image of these eyes in 1000-2500Hz rates. These eye trackers provide the highest accuracy (i.e., the difference between the position a person looked at and the position reported by the eye tracker; cf. validity) and precision (i.e., the difference between several measurements of the same gaze position; cf. reliability) and thus allow for the detection of extremely detailed eye movements, such as minimal movements within a fixation (Engbert & Kliegl, 2003; Martinez-Conde et al., 2020). However, these eye trackers are rather large, require carefully set-up laboratory environments usually involving fixating the participant's head and are thus mostly suited for fundamental research. *Mid-resolution* eye trackers (~ 250-120Hz) are typically attached to a computer screen and can be used without further restricting the participant besides sitting within a reasonable range behind the computer. Hence, allow for a very natural experience for participants when it comes to computer-based tasks. They can be used to study a wide array of research questions relevant to educational sciences, such as reading a text (e.g., Ariasi et al., 2017; Catrysse et al., 2018), studying multimedia instruction (e.g., Mason et al., 2015; Scheiter et al., 2019), searching the web for new information (e.g., Gottschling & Kammerer, 2021; Van Strien et al., 2016), or learning from video tutorials (e.g., Van Marlen et al., 2018; Van Wermeskerken, Ravensbergen, et al., 2018). Hence, these eye trackers are most often used within our field. In 2015 *low-resolution* eye trackers (~ 30-60Hz) entered the market and immediately captured the research community's attention due to their incredibly low prices: while high-resolution eye trackers cost up to 40 000 euros, these devices can be purchased on Amazon for under 260 euros, while still delivering decent quality (Dalmaijer, 2014). Consequently, such eye trackers are currently being used by renown researchers in the field of educational sciences and published in highly acknowledged journals (e.g., Andresen et al., 2019; Stull et al., 2018; Tsai & Wu, 2021). The next logical step is currently taking place: with increasingly improving hardware development of our ubiquitous devices, *webcam-based* eye tracking is being offered by several established eye tracking companies[4]. Several researchers across the globe carefully tested this new approach to eye tracking and are cautiously optimistic about the usefulness of this newest development for educational research (Bánki et al., 2022; Z. Lin et al., 2022; Semmelmann & Weigelt, 2018; Yang & Krajbich, 2021). A rather different type of eye trackers are *glasses*. These are frames that nowadays look like regular, but bulky glasses and have the eye camera and the infrared built in the frames directed towards the eyes and another camera built in the center of the frame facing where the participant is looking at. Afterwards, a video is created from the camera facing the front-view and the eye movements overlaid onto it. Such glasses are very interesting for all educational scenarios that do not take place on a computer screen, such as different forms of teacher-student interactions in the classroom (e.g., Haataja et al., 2019; McIntyre et al., 2019; Minarikova et al., 2021) or natural reading scenarios on tablets vs on print (e.g., Delgado & Salmerón, 2022; Sachse, 2019). The latest developments in eye tracking glasses is, that they are built into VR or AR devices to enable an rather authentic and free in movement, but still controlled environment (Clay et al., 2019; Souchet et al., 2022), such as in training

[4] It is important to note, though, that webcam-based eye trackers do not use infrared lights as all other eye trackers described here, but rough eye models based on an image of the entire face instead. Consequently, their measures are far less accurate.

calligraphy (Limbu et al., 2019) of medical training (J. Y. Lee et al., submitted). In sum, different eye tracking devices are available nowadays, each with their own advantages and drawbacks. It is, thus, important to know their ins and outs to be able to design appropriate experiments fitting these and the according research questions.

Eye tracking devices become increasingly cheap and accessible – to a point when they become ubiquitous?

From Raw Data to Concepts

Irrespective of the concrete eye tracking device, the analysis of its outcome data follows a specific set of steps (for more details on these steps, see Duchowski, 2003; Holmqvist et al., 2011; Jarodzka, 2021).

Step 1. The initial outcome of the *raw data* recordings are long strings of x- & y-coordinates assigned to timestamps per participant.

Step 2. Usually, the first step in analyzing these is to detect diverse *events* in these data: fixations (i.e., moments of relative stillness of the eye), saccades (i.e., rapid, long movements of the eye), smooth pursuit (i.e., relative slow following of a moving object by the eye), blinks (i.e., brief, but regular missing data), and missing data (i.e., missing data that do not match the specific pattern of a blink). Although, one of two-forms of algorithms, which either initially detect fixations (e.g., Salvucci & Goldberg, 2000) or saccades (Smeets & Hooge, 2003), calculate these events, the researchers must decide on the concrete settings for thresholds used to do so. These settings will depend on the stimulus material, but also the eye tracking device used. It is important to note, though, that this decision is not easy as it highly influences the outcomes of the algorithms (Duchowski, 2003; Nyström et al., 2013). An additional data stream provided in the raw data is the size of the pupil. No event detection is performed on this data stream.

Step 3. The following step is relating these eye movement events to certain areas on the stimulus, such as, part of an illustration or a text, or the students' faces in the classroom. These areas are referred to as *Areas-of-Interest*

(AOIs). Again, this is not an easy decision and will influence further results. AOIs can be defined as a grid overlaid over the stimulus (e.g., E. M. Kok et al., 2016; Wolff et al., 2016) or as freeform drawn onto semantic elements of the stimulus, such as one group of students working together or several sentences within a text on the same topic (e.g., Balslev et al., 2012; Mason et al., 2015). All eye movement events will now be summarized across the defined AOIs. In some cases, the first step can be skipped and raw data – so-called 'dwells' – can be directly assigned to AOIs.

Step 4. Optionally, a further step can pursue, on which a *temporal viewpoint* is included, such as in which order certain AOIs were inspected or how often participants switched between certain elements (e.g., J. Y. Lee, Donkers, Jarodzka, & van Merriënboer, 2019; Scheiter et al., 2019) or even to which extent the path of their viewing behavior corresponds to those of others (Dewhurst et al., 2012, 2018; Foulsham et al., 2012; Jarodzka, Holmqvist, et al., 2010). These are measures of the scan path itself. As mentioned already, along each of these steps the researchers take several decisions that ultimately influence the outcomes of the according studies. Hence, it is important that these decisions are thoroughly considered and rooted in educational theories (E. M. Kok & Jarodzka, 2017a) and that each of these decisions is transparently reported (for guidelines on how to report eye tracking studies, see Holmqvist et al., 2022).

Each step of eye tracking data analysis is a decision that ultimately influences the outcomes of the study.

Many measures can be derived from these analysis steps as described above (for an extensive description, see Holmqvist et al., 2011). In Table 1 I mention only those which are relevant for research on educational sciences (Holmqvist et al., 2022; Jarodzka, 2021; E. M. Kok & Jarodzka, 2017a; Rayner, 2009).

Table 1

Eye Movement Measures Capturing Processes Relevant to Educational Sciences

Eye movement	**Definition**	**Exemplary measure**	**Interpretation**
Dwell (Step 3)	Eye is directed towards an area	Total ~time	Intake of information
Fixation (Steps 2&3)	Eye is relative still and takes in information	Mean duration (in AOI)	Processing load
		Total duration in AOI	Intake of information
		Number in AOI	Intake of information
		1^{st}, 2^{nd} pass in AOI	Temporal aspect
		Time to AOI	Temporal aspect
Saccade (Step 2)	Fast relocations of the eyes' focus	Amplitude	-
		Velocity	-
Smooth pursuit (Step 2)	Eye follows a moving object and takes in information	Detection of ~	Intake of information
Scan path (Step 4)	Consecutive fixations and saccades on one stimulus	MultiMatch	Temporal aspect
		Transitions	Temporal aspect
		ScanMatch	Temporal aspect
Blink (Step 2)	Brief closing of the eyes	Mean duration	Processing load
		Frequency	Processing load
Pupil dilation (Step 1)	Size of pupil in relation to emotions and cognitive processing[5]	Mean	Processing load

[5] Of course, the size of the pupil is most sensitive towards light changes. So, I assume in this table that this issue was controlled for.

Some of these measures were already so extensively studied, that we can deduct from the actual numbers which task was given to the participants or how well they do in this task. This is mainly the case for mean fixation durations while reading (Rayner, 2009). For other measures and tasks, of which we have less knowledge, we must remember the following (E. M. Kok & Jarodzka, 2017a): eye tracking measures do reflect cognitive processes, but we usually cannot infer a cognitive process directly from the measure. Hence, we must very carefully design the according experiments and always root our research questions in theories. Additionally, we can adhere to methodological triangulation – i.e., combining eye tracking measures with other data sources, such as verbal reports – to getter a better grasp of the underlying cognitive processes (Van Gog & Jarodzka, 2013).

CHANCES

Eye tracking research stretches over a wide field of areas, ranging from engineering of novel hardware, development of innovative software, fundamental research of human vision, to applications of eye tracking in neurology, clinical psychology, reading research, language comprehension, cognitive psychology, marketing, and usability[6] , and education is just one of them. Albeit, the use of eye tracking in the field of educational sciences has been growing over the past decades (for comprehensives reviews, see Alemdag & Cagiltay, 2018; Coskun & Cagiltay, 2022; Jarodzka et al., 2017; Lai et al., 2013; Strohmaier et al., 2020). The number of articles found in Google Scholar with the search terms 'eye tracking' and 'education' yielded 7.240 hits before 1979[7], 22.600 hits the two decades later (1980 – 1999), and 274.000 hits over the past two decades (since 2000)[8]. This comes as no surprise, because eye tracking enables us to study how learners perceive and how they process new information (pp. 24), but also how they retrieve information from their memory (pp. 37). And how drastically these processes change with increasing expertise in a specific field (pp. 45). This research helps us to form theories on human information processing, but also to design efficient instruction, valid testing, and support professionalization.

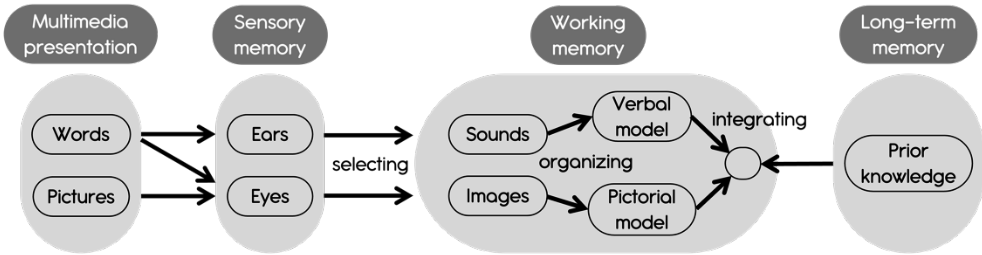
LEARNING

The aim of learning is to gain new knowledge or to acquire new skills. Thanks to decades of research, we know quite well how learning happens (from more details, see Jarodzka, Boshuizen, et al., 2013): we learn by processing information through various stages of our sensory, perceptual and cognitive system (3-storage-model by Atkinson & Shiffrin, 1968). Initially, our eyes (or ears) pick up information (see pp. 10) which enters the sensory register. This register can hold many information elements, but only for several hundred milliseconds (Sperling, 1960). Once we direct our attention to certain information elements, these enter our working memory (Baddeley, 2012). This is where the magic happens! Here we can operate this information in all kinds of ways. The bad news is that it is very limited in terms

[6] If you would like to be acquainted with these fields, I highly recommend you the two most important eye tracking conferences, namely European Conference on Eye Movements (ECEM) or Eye Tracking Research and Applications (ETRA).
[7] 1900 – 1979
[8] Per July 2022

of how much information it can hold (Miller, 1956; Peterson & Peterson, 1959). The good news is that this memory has two “drawers”, of which one can be filled with pictures and the other one with words (Baddeley, 2012; Paivio, 1969). Finally, this information can be stored in long-term memory, which has unlimited capacity, but we do sometimes run into the problem of retrieving it. These findings formed the basis of two key learning theories, namely the *Cognitive Load Theory* (Chandler & Sweller, 1991; Sweller et al., 2019a) and the *Cognitive Theory of Multimedia Learning* (Mayer, 2021).

Figure 9
Learning from Multimedia According to Mayer (2021)



Note. From “Cognitive theory of multimedia learning”, by R. Mayer, 2021, *The Cambridge Handbook of Multimedia Learning*, p. 57-72 (DOI: 10.1017/9781108894333.008).

According to the *Cognitive Theory of Multimedia Learning* (Mayer, 2021), the above-mentioned considerations translate into learning as follows (Figure 9): the learning material is presented as multimedia, that is, a combination of text and pictures. The picture elements enter sensory memory via the eyes, while the verbal elements enter it either via the eyes (if they are presented as written text) or via the ears (if they are presented as audio). Then the learner *selects* verbal and pictorial elements for further processing. In working memory, these elements are organized into a verbal and a pictorial model. It is important to note that during this processing, all verbal elements (irrespective whether they were presented as audio or as writing text) and all pictorial elements are *organized* into two mental models. Finally, both models are *integrated* together as well as with prior knowledge retrieved from long-term memory. The idea of this theory is that in order to learn, one must actively engage in these three processes: selecting relevant information, organizing them into mental models, and integrating them with prior knowledge. A recent review on 57 eye tracking studies on multimedia learning (Coskun & Cagiltay, 2022) showed that eye tracking measures can be and are directly related to these three processes (Table 2).

Table 2

Processes of Learning and Eye Tracking Measures Capturing These

Learning process	Eye tracking measure
Selecting	Time to first fixation First five fixations Proportion of fixation duration Proportion of fixation count First pass time
Organizing	Total fixation count Total fixation duration Dwell time Average fixation duration Fixation position Pupil size Blink rate
Integrating	Number of transitions Number of saccades Scan paths
Mental effort	Pupil dilation Blink rate Transitions Fixation duration Fixation frequency

The *Cognitive Load Theory* (Chandler & Sweller, 1991; Sweller et al., 2019a) zooms in on the capacity limitations of working memory. This theory claims that working memory can be occupied with relevant processes, such as the ones just mentioned (germane load), or with unnecessary processes that do not lead to learning (extraneous load). Both loads add up to one overall load of working memory. Certain eye tracking measures have shown to react to the amount of this load (Table *2*), namely the dilation of the pupil (Hess & Polt, 1964; Szulewski et al., 2017), the rate of blinking the eyes (Eckstein et al., 2017; Vanneste et al., 2021), the duration (Korbach et al., 2016; Park et al., 2015) or frequency of fixations (Van

Orden et al., 2001; Zelinsky et al., 1997), or transition rates between different AOIs (J. Y. Lee, Donkers, Jarodzka, & Van Merriënboer, 2019; J. Y. Lee et al., 2020, 2021).

Sometimes when studying processes of learning, the specific measures described in Table *2*, however, do not entirely match what you want to investigate. In such cases, it is necessary to derive different measures directly from your specific research questions, while keeping concrete learning task and material in mind. Indeed, eye tracking can tell us even more about different cognitive processes, such as encoding and decoding information from memory (Foulsham et al., 2012), the difficulty of a given task (Dewhurst et al., 2018), and other cognitive and metacognitive processes relevant to learning (Jarodzka et al., 2017; Van Gog & Jarodzka, 2013). In this way, eye tracking has been already widely used to study diverse aspects of learning. For instance, we know already plenty about visual processes during *reading* and how they change with different difficulties of the text and the abilities of the readers (e.g., Ariasi et al., 2017; Rayner, 2009), up to combining reading of several texts (e.g., Jarodzka & Brand-Gruwel, 2017), or how these processes change when reading in print or on computer screens (e.g., Delgado & Salmerón, 2022; Jian, 2022; Latini et al., 2020). We also know already a lot about how learners deal with *multimedia* material including different combinations of text and pictures, such as the World Wide Web (e.g., Argelagós et al., 2018; Lewandowski & Kammerer, 2021), online learning (e.g., Mu et al., 2019), multimedia learning (e.g., Liu, 2021; Scheiter et al., 2019; F. Wang et al., 2020), or self-regulated learning with task databases (Nugteren et al., 2018).

A specific multimedia learning material that has gained plenty of attention from educational research over the past years are educational videos (Alemdag & Cagiltay, 2018; de Koning et al., 2018; Mayer et al., 2020). This trend has been amplified through the COVID-crisis, during which teachers worldwide made such videos for their emergency remote teaching. Yet again, eye tracking has helped us to better understand certain aspects of learning from videos, such as the effect of the teacher being visible in a video (Stull et al., 2018; Van Wermeskerken, Ravensbergen, et al., 2018; Zhang et al., 2021). In the following, I will focus on a specific type of educational video: tutorials where the teacher is not visible, but we still want attention guidance from the teachers to help the students focusing on the important information – Eye Movement Modeling Examples.

Eye Movement Modelling Examples

A very powerful way of learning is to observe and to imitate someone; it is so deeply rooted in our system that even two weeks old newborns imitate facial expressions and manual gestures of adult models (Meltzoff & Moore, 1977). Albert Bandura has shown, in a series of experiments, that observed behavior does lead to learning and imitating this behavior even in the absence of the model (Bandura, 1986). In particular, he and his colleagues demonstrated that children imitate earlier observed behavior of adults towards a toy (Bandura et al., 1961) even if they observed only a video recording of this behavior (Bandura, 1963, 1965). Decades of research following these studies proved that studying how a model executes a task – also referred to as example-based learning or modelling – is more efficient than learning by problem-solving alone (Kirschner et al., 2006; Renkl, 2010; Van Gog & Rummel, 2010). For certain tasks, it is not possible to observe the crucial steps and processes of a model directly as these processes are "hidden in the model's head". Imagine for instance solving a mathematical equation. In such cases, the model must *speak out loud* what they are doing (i.e., which steps they take) and why (cognitive apprenticeship: Collins et al., 1989; process-oriented modeling examples: Van Gog et al., 2004). For some tasks, this is not the entire story, though. When executing tasks with a strong visual component, such as diagnosing an X-ray or classifying a zoological species, it is also important to know, what visual element the model is referring to – a process that is difficult to put into words (Ericsson & Simon, 1993). This is particularly challenging as experts and beginners differ tremendously to what elements they visually attend to [9] (Gegenfurtner et al., 2011; Jarodzka et al., 2017; Sheridan & Reingold, 2017). For such tasks, we created *eye movement modelling examples* (EMME: Van Gog et al., 2009). EMME are video recordings of task material with eye movements of a model executing this task, superimposed on it (as depicted in Figure 2 and 3). Depending on the task, the model may also manipulate the material. Usually, these recordings are accompanied by the above-mentioned verbal explanations on what and why they are doing.

[9] See also chapter 'Development of Expertise'

The rationale behind EMME is twofold. First, following someone else's gaze comes inherently natural for us: humans have a white sclera (i.e., the white part of the eye), so we can easily infer which direction someone else looks at (our neural system recognizes the eye's direction easily: Boyarskaya et al., 2015). This ability is present in newborns as young as one week (Farroni et al., 2002). The need to establish such joint attention with another person, i.e., both looking in the same direction, is so strong that even when we know we are being misdirected, we still cannot help looking there (Driver et al., 1999). Furthermore, establishing joint attention is a mechanism for learning: young infants learn the meaning of words, thus language, by following the gazes of adults (Baldwin, 1995; Bloom, 2002; Scaife & Bruner, 1975). Interestingly, it seems that this mechanism might be transferable to displaying eye movement recordings: eye tracking research has shown already decades ago that displaying eye movements of someone else guides the viewers visual attention to these (Velichkovsky, 1995). Hence, we can assume that EMME have the potential to guide the learners' visual attention to what the model is referring to. Second, showing the visual focus of the model enables the learner to infer what they are referring to in their explanation and thus to establish 'joint attention' (Butterworth, 1995). Instead of scanning the screen for what the model might be talking about and thus, not being able to integrate the visual and auditory information and on top of that likely missing new information, the learner is smoothly guided through the screen and can focus on the spoken explanation. This in turn, yields a better understanding of what the models says (Grant & Spivey, 2003; Richardson & Dale, 2005). Again, we can assume that EMME lead to a better understanding of what the model is saying. Indeed, in two studies we showed that EMME can be a successful instructional material (Jarodzka et al., 2012; Jarodzka, Van Gog, et al., 2013): We showed that displaying the models' eye movements guided participants' visual attention to follow the models' visual focus while studying the EMME videos. Moreover, when classifying/diagnosing new video examples (i.e., transfer), participants in the EMME conditions looked quicker and longer at relevant areas of the new videos and interpreted them more correctly. Two recent meta-analyses on 25 and 72 EMME studies, respectively, confirmed our findings (Emhardt et al., submitted; Xie et al., 2021). Hence, we can conclude:

EMME guide the learners' visual attention to what the model is referring to, help them to better understand the associated verbal explanation, and thus, to learn to visually inspect and interpret similar tasks.

I must admit, though, that these effects were not as straight forward, hence, they opened new research questions. First, these effects varied with how the models' eye movements were *displayed*: either by using the manufacturers' provided replay options displaying eye movements as moving dots overlaid on the video or by rendering the video in such a way that only the areas attended by the model were visibly sharp while the rest of the video appeared blurred (i.e., as a spotlight: Dorr et al., 2010; Nyström & Holmqvist, 2008). Second, in our very first attempt to implement EMME as an instructional tool was not successful (Van Gog et al., 2009) in that participants learned better *without* the model's eye movements being displayed and experienced the highest mental effort after having studied EMME. In this very first study (Van Gog et al., 2009) the model was trained in the task and asked to behave in a didactic manner, while in the other two studies (Jarodzka et al., 2012; Jarodzka, Van Gog, et al., 2013) we used true experts and an explicit procedure to ensure that they indeed would behave didactically, which in itself could have influenced our outcomes. This yields the assumption that the effectiveness of EMME depends on the way *the model* is instructed. Third, in Van Gog et al. (2009) we used a small computer game similar to the Tower of Hanoi as a learning task (i.e., procedural task), while the two later studies focused on the training of visually complex tasks (i.e., perceptual tasks), namely in classifying zoological locomotion patterns (Jarodzka, Van Gog, et al., 2013) and diagnosing infants' motion patterns during seizures (Jarodzka et al., 2012). Thus, we concluded that the effectiveness of EMME depends on the *type of task* being taught. Many more EMME studies have been conducted since then (for recent reviews, see Emhardt et al., submitted; Krebs et al., 2021; Xie et al., 2021) indicating that also several *learners' characteristics* might play into the effectiveness of EMME. In the following I will discuss, what we already do know, where further research is necessary on these issues and which other research questions emerged.

Showing the Model's Eye Movements

A key component of EMME are the eye movements of the model superimposed on the task material itself. These eye movements are commonly visualized either as scan paths or as spotlights, of which both can be either static or dynamic (see Figure 2). Scan path visualizations show fixations as dots and saccades as connecting lines between these dots. Several aspects of scan path visualizations can be varied, such as the color of the visualization, its opacity and changes in size depending on the duration of each fixation – or a lack thereof. Such scan paths can be shown as a static overlay over an image or dynamically as a single dot moving across the screen over time. In the latter case, we can also vary for how long the 'trail' – that is the trace of previous saccades and fixations – remains visible. Spotlight visualizations, on the other hand, retain the area, where the eye movement is located, while the rest of the image or video is altered in such a way that it appears less visible. This ranges from simply darkening this area (Krebs et al., 2019, 2021) to reducing its color and contrast over space and time (Nyström & Holmqvist, 2008; Vig et al., 2012). The latter is a video rendering technique that reduces the size of the video, but also subtly guides the viewers' eye movements to the unaltered areas (Dorr et al., 2010). Both visualizations of the model's eye movements can be either displayed static, i.e., the entirety of the recorded scan path displayed at once over an image or a screenshot, or dynamic, i.e., each fixation is displayed consecutively and disappears (either immediately or it leaves a brief trace in the form of a thin line). People can interpret such dynamic and scan path displays of eye movements more correctly than static and spotlight ones (E. M. Kok et al., subm.; Van Wermeskerken, Litchfield, et al., 2018).

The question is: which works best for learning? Unfortunately this question is difficult to answer as most EMME studies thus far used a dynamic scan path visualization (Emhardt et al., submitted). Few exceptions, give us first hints, though. Our own initial findings from two studies (Jarodzka et al., 2012; Jarodzka, Van Gog, et al., 2013), where we directly compared these two visualization versions suggest that the spotlight better guides the learners' visual attention to follow the model's eye movements while watching the EMME. Also, having studied the spotlight version of EMME lead to quicker identifying the crucial elements when watching new videos and keeping focused on these, compared to when having studied scan path EMME. Hence, reducing the information of the videos by temporarily blurring less relevant information, guides visual attention more smoothly and helps to focus on relevant aspects of the task. On the other hand, the interpretation of these elements seemed to improve more in the scan path condition, which still enabled a holistic overview of the entire video (de Koning & Jarodzka, 2017; Jarodzka et al., 2017). In a collaborative visual search task, Zhang et al (2017) compared several visualization techniques and also found that spotlight visualizations of eye movements yield the most efficient visual search, while scan path visualizations result in the best search performance. Recently, Brams et al. (2021) also compared these two visualization techniques, albeit as feedback tools. They found no effect of EMME (as compared to a control training without visual feedback) on visual search on new videos, but a benefit for the scan path EMME on their interpretation (here: detection of pathologies on a lung X-ray). Thereby, partially confirming our findings. In a most recent study, we compared these two visualization techniques in a real-life setting of a lecture room where a teacher was live teaching looking at a computer screen and all students could follow the lecture slides on their individual screens, either with a spotlight or scan path EMME or no eye movement visualization of the teacher (Niehorster et al., in prep.). We found that the spotlight guided the students' visual attention to the teacher's eye movements most, followed by the scan path and both EMME did that more than a control version, but we found no effects on learning performance. In sum, we have sufficient evidence that the type of eye movement visualization in EMME matters, but more research is necessary to be able to make clear statements about these effects. Currently, the most likely postulation is that:

Spotlight EMME best guide visual attention and yield most efficient visual search, while scan path EMME result in best learning outcomes.

Characteristics and Behavior of the Model

Next to the question of how to visualize the model's eye movements is *whom* to ask to be a model and *how* to instruct them to behave? In terms of what characteristics an appropriate model should have (cf. Van Gog & Rummel, 2010) reviews show that most EMME-models are experts, with some also being the researchers themselves (Emhardt et al., submitted; Xie et al., 2021). Few studies used novices or peers as EMME-models, but those did not find a positive effect on learning (Emhardt et al., submitted) although one study showed a positive effect on performance on the task at hand (thus not on learning) irrespective of the model being an expert or a novice (Litchfield et al., 2010).

The second question is whether experts can serve as models demonstrating their regular behavior. Knowing, how much experts differ from novices (see pp. 45), we decided in our earlier studies to take several precautions in implementing EMME. First of all, we studied whether experts substantially differed from novices when inspecting the respective tasks (Balslev et al., 2012; Jarodzka, Scheiter, et al., 2010). Next, when constructing EMME in these domains, we ensured to choose domain experts, who had substantial teaching experience (Jarodzka et al., 2012; Jarodzka, Van Gog, et al., 2013). Finally, we applied a specific procedure to instruct these experts to behave in a didactic manner (de Koning & Jarodzka, 2017; Jarodzka et al., 2017): to achieve a close relation between the eye movements and what the model is talking about, they received time to first get acquainted with the task material itself (Richardson & Dale, 2005). Then, to shift their focus from their own expert view to the perspective of a novice, we provided them with a checklist with the following questions (Jucks et al., 2007): Will a student understand each term that you use in our description? Is the task explained in comprehensible enough terms for students? Is it explained in enough detail? Did you provide all necessary information for a student? Is all information that you provide important? At last, they could revise each recording to achieve optimal modelling examples. Although these EMME implementations were successful (Jarodzka et al., 2012; Jarodzka, Van Gog, et al., 2013), we could not say to which extend this procedure added to their effectiveness. In a recent study, we could show that this procedure does alter experts' eye movements so they become more similar to those of novices in terms of slowing-down, but less similar in terms of their strategies showing ultimately a clearer and calmer correct approach to the task (Emhardt et al., 2020). In a follow-up study, we tested whether these differences also translate into effects on learning outcomes for students watching these videos, but we found no significant effects (Emhardt et al., 2022). However, it is difficult to draw conclusions as no other study has investigated this factor directly with more than 50% not even reporting on these details (Emhardt et al., submitted). Ultimately, the little empirical evidence that we do have thus far, indicates that:

The nature and the behavior of the model in the EMME seems not to affect learning outcomes.

Type of Learning Task

Two recent meta-analyses indicate that the effectiveness of EMME might also depend on the type of the learning task (Emhardt et al., submitted; Xie et al., 2021). Xie et al (2021) show via a meta-analysis that EMME were most effective for non-procedural tasks. Emhardt et al (submitted) showed most positive learning effects for visual classification tasks, visuo-motor tasks, and interestingly for text processing, but not for problem-solving tasks. I would like to argue that there might be another underlying factor of these findings, namely the visual complexity of the learning material itself (Jarodzka et al., 2017). Indeed, those tasks that these reviews have categorized as being procedural tasks used visually simpler material (e.g., geometrical problems), while the other tasks often used visually rich material (e.g., medical images of human anatomy). This assumption is corroborated by our own research: While we found clear positive effects of EMME on visually complex material (Gegenfurtner, Lehtinen, et al., 2017; Jarodzka et al., 2012; Jarodzka, Van Gog, et al., 2013), we could not find them for less visually complex material (Van Gog et al., 2009; Van Marlen et al., 2016), unless visual complexity was increased by ambiguous verbal explanations of the model (Van Marlen et al., 2018). Irrespective of what aspect of the task is driving, we can conclude the following:

The effectiveness of EMME depends on how the model's eye movements are displayed, how the model is instructed to behave, what type of task is being taught.

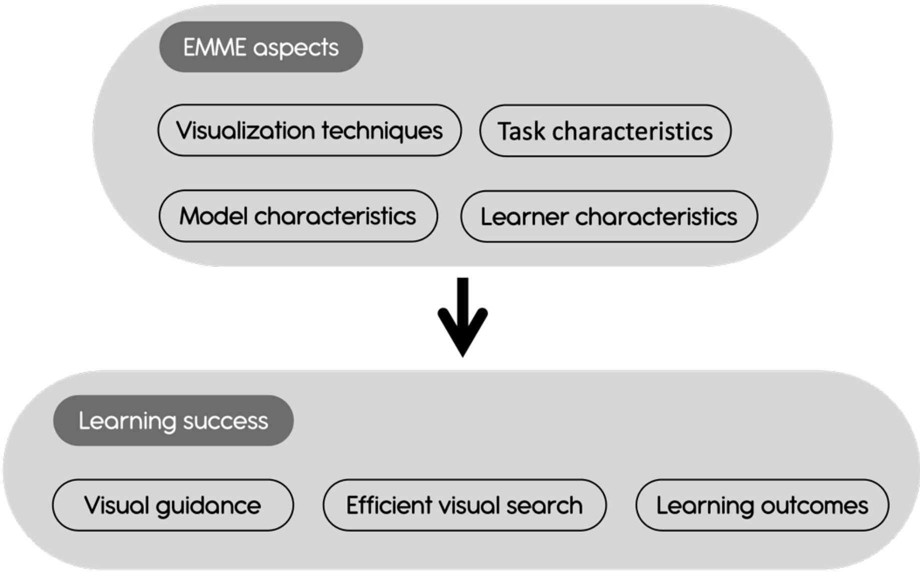
The Learner and Their Context

The research on EMME is still rather young; hence, many questions remain unanswered. One aspect of EMME that we have not investigated thus far, is the perspective of the learner themself. One of the most important learner characteristics for multimedia learning, is the how much the learner already knows about a certain topic, that is, their *prior knowledge*. From research on multimedia learning we know that the learner's prior knowledge is the most important characteristic to consider when designing instructional material (Mayer, 2018), which can entirely change the playing field of how instruction works (e.g., Bokosmaty et al., 2015; Rey & Fischer, 2013). Indeed, both literature reviews mentioned above have explicitly looked into the effects of leaners' prior knowledge on the effectiveness of EMME (Emhardt et al., submitted; Xie et al., 2021). And while Emhardt et al. (submitted) do see that it is potentially important, Xie et al. (2021) could not find support for this in their meta-analysis. However, this lacking meta-analytical effect could also be due to the small amount of studies systematically taking this aspect into account (e.g., Chisari et al., 2020; Krebs et al., 2021; Litchfield et al., 2010; Van Marlen et al., 2018). Hence, we should keep prior knowledge in mind as a potentially important learner characteristic for the effectiveness of EMME.

In sum, we saw that EMME can affect three aspects relevant to learning: (i) how well learners' can follow the model's visual focus, (ii) how efficient learners can visually search relevant elements in test tasks, and (iii) their learning outcomes. We also saw that, four features of EMME influence each aspect differentially, namely (a) how the eye movements of the model are visualized, characteristics of (b) the model, (c) the task, and (d) the learners. However, more research is necessary to complete this picture (Figure 10) and to also investigate to which extend, these EMME aspects might interact with each other (i.e., maybe a certain visualization technique is more suited for a specific learner group or a specific type of task).

Figure 10

Aspects of EMME that Influence Factors of Learning Success



Testing

Tests form the basis of life-changing decisions, such as graduating a class, reaching a diploma, receiving the driver's license, or failing. These decisions are not only important for the individual, but also for society. Imagine, having a heart surgery by a surgeon, who had only mediocre scores on the final exam or entering a plane operated by a pilot who scored only mediocre accuracy during test flights. But test scores are crucial already early on in education: They enable teachers to objectively assess their students' current knowledge and skill level and adapt their instruction accordingly (Shute & Rahimi, 2017). There are many ways to test, but computer-based testing (CBT) is on the rise, both on internationally (e.g., Program for International Student Assessment: PISA, Trends in International Mathematics and Science Study: TIMSS, Programme for the International Assessment of Adult Competencies: PIAAC) and nationally (e.g., Dutch Centre of Educational Measurement: CITO, 10voordeleraar – landelijke kennistoetsen, dia-taal bv). The potential of CBT is increasingly recognized among scholars from psychology and education (Bennett, 2018; Drasgow, 2015) – with some even believing that this will be the future of testing (Scherer et al., 2017). Next to administrative advantages, such as automated scoring (Bennett & Zhang, 2015; Gierl et al., 2014; Veldkamp, 2015), it holds potentials for educational sciences: CBT enables us to investigate the processes underlying test-taking-behavior to better understand the testees' strategies and behavior (Cope & Kalantzis, 2016; Greiff et al., 2015, 2016). Moreover, CBT allows us to measure new aspects of a skill by providing more authentic tasks than paper-based tests could (OECD, 2017), which is also the potential of CBT being more valid than traditional paper-based tests (for difficulty to achieve high validity in traditional test forms see Brown & Abdulnabi, 2017). CBT can become authentic through combining pictures (static, dynamic, interactive) with written or spoken text (i.e., multimedia, see Mayer, 2021; Sweller et al., 2019a). For instance, testing a medical student's ability to perform resuscitation based on an interactive simulation (J. Y. Lee, Donkers, Jarodzka, & Van Merriënboer, 2019) would not be as valid with paper-based tests (cf. the importance of authentic tasks for evaluating expertise in professions: Ericsson et al., 2018). Another benefit of using multimedia in CBT is that testees perceive them as more engaging, effective, and entertaining compared to paper-based tests (Azabdaftari & Mozaheb, 2012; Chua, 2012; Chua & Don, 2013), which has a positive influence on their motivation (C.-C. Lin & Yu, 2017).

However, only because something is technically possible, does not mean that we must use it in education (Mayer, 2019). On the contrary, poorly designed multimedia in CBT could distract and overwhelm testees and hamper their performance (Květon et al., 2007; Parshall et al., 2002; Prisacari & Danielson, 2017). And building valid CBT is challenging (Chua & Don, 2013; Květon et al., 2007). Surprisingly, there are no guidelines on how to use multimedia in testing; consequently, researchers argue for a theoretical model of CBT to build such guidelines upon (Bennett, 2018; Kirschner et al., 2016).

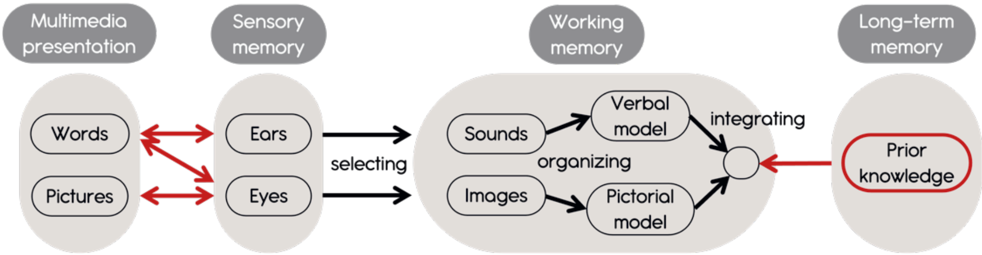
Using multimedia in computer-based testing is both, promising, but also challenging.

Multimedia Testing

It might seem appealing to apply design guidelines from multimedia learning to testing, but learning is not testing, and testing is not learning. Hence, there are several reasons why such a generalization would be problematic. First, the aim of learning is to process *new* information and to construct knowledge in working memory that then will be stored in long-term memory (Sweller et al., 2019a). The aim in testing, however, is to retrieve *existing* knowledge from long-term memory to determine, what someone has learned as valid as possible (Alexander, 2018; Lindner, 2021; Mayer, 2002). I suggest revisiting the theoretical model presented in the last chapter (Figure 9) and applying it to testing with multimedia, where the aim is to recall and apply existing knowledge (Figure 11). When encountering a multimedia testing item, initially information enters from the sensory register to working memory. But once the according prior knowledge in long-term memory is activated in working memory, it guides any further intake of information. Hence, the testee actively searches for the information they need. Hence, the entire information flow through the model is reversed and more iterative.

Figure 11

The Cognitive Theory of Multimedia Learning Applied to Multimedia Testing



Note. Based on "Cognitive theory of multimedia learning", by R. Mayer, 2021, *The Cambridge Handbook of Multimedia Learning*, p. 57-72 (DOI: 10.1017/9781108894333.008).

To draw meaningful conclusions on this model, though, it is inevitable to measure how testees *process* test items. This necessity to research the processes underlying testing is emphasized by both, leading researchers from the testing community (Bennett, 2018) as well as from multimedia learning (Mayer, 2019).

To understand how to design multimedia testing, we must study the processes underlying it.

Lindner (2021) also discussed in a recent literature overview of this still young field, the effects of the type of the picture used in multimedia testing (e.g., decorative, representational, organizational), the placement position of the picture in the test item (i.e., in the item stem vs in the answer options), and the study domain on testees' motivation, correctness of their responses, how long they take the test items, and how they process them (i.e., eye tracking). As potential moderators she identified individual characteristics of the test-takers and the concrete design of the multimedia within the test item. In the following, I would like to focus on the latter by examining how the design of the multimedia in test items effects how test-takers process these items.

Multimedia Design of Test Items Matter

In 2010 we began a cooperation with CITO (www.cito.nl), one of the main suppliers of the yearly standardized school tests in the Netherlands. Their test items are constructed with the help of large consortia including teachers, test designers etc. where the content, phrasing, and choice of provided information is discussed extensively, but not necessarily the concrete design of these test items. Their tests make full use of the digital possibilities including videos, colorful pictures, additional text information in pop-up windows etc. In their test item design of 2010 (arts exam), the explanatory text (i.e., the item stem), the question, and the answer field were located on the right-hand side, while all additional information was located on the left-hand side, for technologically pragmatical reasons. From theoretical models on multimedia learning (Mayer, 2019; Sweller et al., 2019a) this is a disadvantageous way of presenting information as it causes split attention (Ayres & Sweller, 2021; Chandler & Sweller, 1992). That is, the testee is forced to spend limited cognitive resources on searching and integrating related information. As a result, too few resources are left for solving the task (Makransky et al., 2019). Assuming that the same would be true for testing, we created an alternative, integrated test item design, where information is placed where it is needed (Figure 12).

Figure 12

Exemplary Test Item from the CITO Test. The Original, Split (Left) and the Adapted, Integrated Design (Right).

Note. All additional elements could be opened in a pop-up window (and some could be played). Adapted from "Avoiding split attention in computer-based testing: Is neglecting additional information facilitative?", by H. Jarodzka, N. Janssen, P. Kirschner, and G. Erkens, 2015, *British Journal of Educational Technology*, pp. 808 & 809 (http://doi.wiley.com/10.1111/bjet.12174).

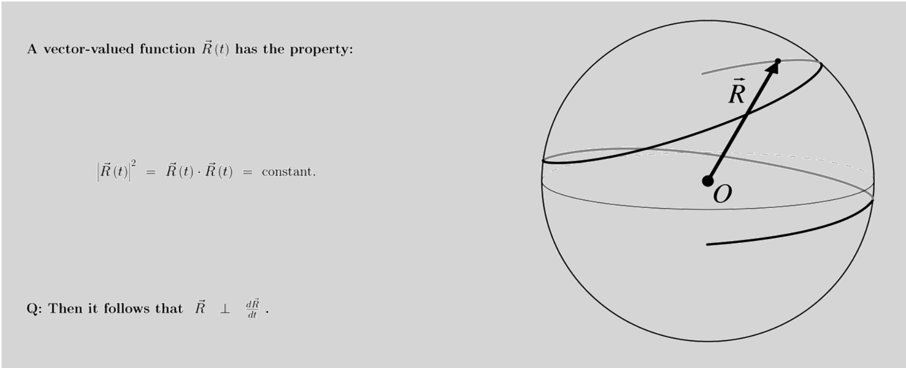
Contrary to our expectations, the testees performed worse in the integrated design. Eye tracking data revealed that testees looked longer at additional information and less at the question (i.e., amount and total duration of fixations on these screen areas) in the integrated design and did not make the expected increased search and integration of information (i.e., eye movement transitions between areas on screen) in the split design. Thus, testees neglected most of the information on the left hand-side in the original design, while they did process all information in the adapted design. At the same time, this design had detrimental effects on their test scores (Jarodzka, Janssen, et al., 2015). Even though this study raised many questions, it also made two points clear:

> We cannot simply impose design guidelines for multimedia learning onto testing and we must measure how testees process test items to truly understand what is going on.

We confirmed these conclusions in higher education in the domain of vector calculus in mathematics (Ögren et al., 2017). There, we compared test items with and without a representational graph (i.e., representing information provided in the text in a pictorial manner). These items presented some background information, a formula, and a statement about this formula, which had to be either confirmed or denied (Figure 13). Performance data showed no positive effect on correctly answering the test items, but rather a bias towards confirming the statement in the condition with the graph. Eye tracking data revealed that when a graph was present, test-takers looked less at the background text and the question, while looking at the graph was not positively related to performance. Looking more at the question and often transitioning between the question and the graph, was related to higher performance on those test items. Hence, only an active and critical use of the multimedia elements, improved test-takers' performance.

Figure 13

Multimedia Test Item Including Graph and Formula



Note. Adapted from “There’s more to the multimedia effect than meets the eye: is seeing pictures believing?”, by M. Ögren, M. Nyström, and H. Jarodzka, 2016, *Instructional Science*, pp. 263-287 (http://link.springer.com/10.1007/s11251-016-9397-6).

In our latest publication on this topic, we again worked together with CITO and decided to apply several multimedia guidelines to their authentic multimedia test items at once (Dirkx et al., 2021). When improving test items on several aspects of multimedia (e.g., avoiding split-attention, redundancy, seductive details), test-takers’ performance improved in comparison to the original test items. In the original test items, test-takers paid more attention to the background text (item stem) and pictures, while experiencing higher mental effort. In the adapted items, however, they paid more attention to the question and to the answer options. It is important to keep in mind that all changes to the test items we made, did not change the information provided in them, but merely their layout.

It is possible to change how testees processes and how they perform on multimedia test items by merely changing the layout of these items.

Based on our findings, but also on similar findings from other research groups (e.g., Lindner, 2020; Lindner et al., 2017; Saß et al., 2017), we stated a plea for more systematic research to develop a theoretical model of human information-processing of multimedia during testing, so we can derive concrete design guidelines from this model (Kirschner et al., 2016). Recently, several key researchers affirmed our plea (Bennett, 2018; Mayer, 2019).

Factors that Likely Play a Role in Multimedia Testing

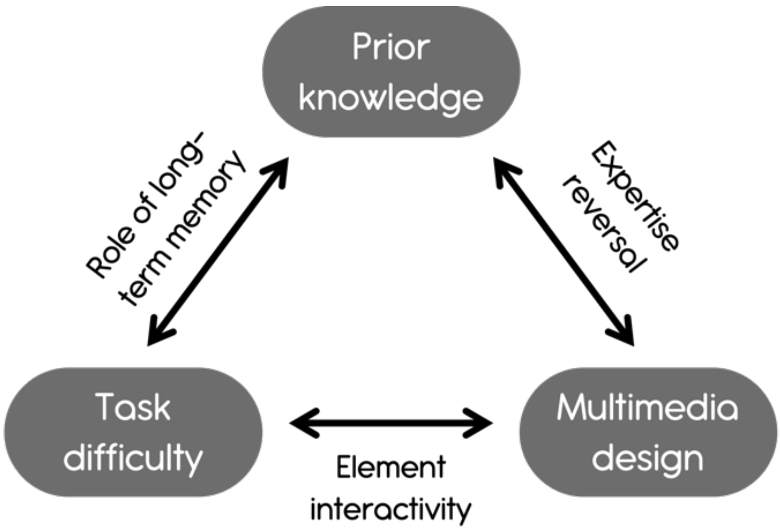
In our latest study, we have shown that lowering *extraneous processing* that is caused by poor multimedia design leads to higher test performance (Dirkx et al., 2021). A recent review (Mayer, 2019) showed that the most powerful ways to achieve this are by spatially (and temporally) integrating related information (Ayres & Sweller, 2021; Fiorella & Mayer, 2021; Mayer & Anderson, 1992; Tarmizi & Sweller, 1988), omitting interesting, but unnecessary information (Fiorella & Mayer, 2021; Harp & Mayer, 1998; Park et al., 2011), or by avoiding duplication (Kalyuga & Sweller, 2021). Hence, it would be interesting to study further, which of these guidelines contributed most to this performance enhancing effect. However, the idea to lower extraneous processing stems from the design aims in learning to make it as easy as possible for students to process information and store it in long-term memory. This, however, is not the aim of testing. In testing, we want to discriminate between testees of different skill-levels. Hence, the aim of multimedia design in testing *could* also be to make functional use of extraneous load to discriminate between better and worse testees (cf. Kirscher, Park, Malone, & Jarodzka, 2017).

Another factor in multimedia testing is likely to be the *difficulty of the test item*. The difficulty of a task called ‘intrinsic’ or ‘essential’. Intrinsic processes result from the amount and interactivity of elements within a task (Mayer, 2019; Sweller et al., 2019a). Element interactivity is a ‘compound effect’ (Sweller et al., 2019a), meaning that it influences multimedia design effects (as those described in the last paragraph), in that they are only effective for difficult tasks (e.g., Chen et al., 2015). However, element interactivity can also cause extraneous processing, showing the interrelation between multimedia design and task complexity.

Finally, the difficulty of a task is not an objective measure, but only meaningful in relation to what someone already knows (i.e., prior knowledge; Sweller et al., 2019b). Indeed, prior knowledge has shown to interact with task difficulty (Blayney et al., 2016). We know from research on expertise that experts can solve difficult tasks that novices are completely overwhelmed with (Ericsson et al., 2018; Jarodzka et al., 2017). Mayer (2018) even refers to prior knowledge "the single most important individual difference dimension for educational practice" (p. 177). Yet again, prior knowledge yields a compound effect – the 'expertise reversal effect' – stating that multimedia design effective for novices become counterproductive with increasing expertise (e.g., Bokosmaty et al., 2015; Jiang et al., 2018; Rey & Fischer, 2013). This effect can be seen as general variant of the element interactivity effect, emphasizing the interrelation between all three factors (Chen et al., 2017; cf. Figure 14).

Figure 14

The Three Main Factors of Multimedia Learning and their Interrelations



Development of Expertise

In a world where facts can be 'alternative', where objective news can be declared 'fake', where well-established scientific knowledge is questioned on the grounds of individual preferences and perspectives, and where groundbreaking scientific advances that can save our lives are rejected due to false skepticism, we cannot simply 'educate ourselves' as some shrill voices claim on social media. Most problems of our lives are so complex that it is impossible to grasp them. Hence, we as society rely on people specializing and devoting their lives to certain topics, master and hone their skills so that they become a source of our society's wisdom: reliable experts.

But expertise is not something for a small elite; it is a stage we all can achieve be it in our jobs, our hobbies, or our sports. On the upcoming pages, I describe what makes an expert and how you can become one. I thereby focus on *visual expertise*. That might sound very specific, but I will show, for how different domains it does play a key role.

How Experts Process Information

I just made the bold statement that everyone can become an expert in some area. Once you understand how many researchers in our field define expertise, you might be more inclined to believe me: an expert is someone, who *repeatedly* performs *better* than others and does so on a set of tasks that are *representative* for a certain domain (Ericsson et al., 2018; Ericsson & Lehmann, 1996; Ericsson & Smith, 1991). That means, in the following, I only consider someone being an expert, who objectively is better in a certain task than others are, is so continuously and not only once by accident, and who does that on tasks that clearly represent certain aspects of a profession (or hobby). I am aware that this excludes expertise given by social status or in ill-structured domains where 'better' performance is difficult to establish objectively (e.g., creativity or superior taste in drink, food, or art; for a different take on expertise, see Shanteau et al., 2002; Weiss & Shanteau, 2014). I am not saying that these people are not experts – think for instance of an artist such as Picasso, who started to paint in ways that seemed simpler from a technical perspective, but exactly this made them the more revolutionary – as was decided by arts critics and art dealers. This type of expertise requires a different scientific approach than what I am going to present to you today (see: Duchatelet et al., n.d.). Hence, the definition of expertise for the upcoming chapter, is:

An expert repeatedly outperforms others on a set of representative tasks.

A person, who can do so, is not bound by the limited information processing system described in the past two sections; these rules simply do not apply to them anymore. Indeed, decades of research have shown that the more a person knows about a topic, the less they are restricted by the limitations of working memory and the more long-term memory plays a role in information processing. As large amounts of knowledge are stored in long-term memory, this knowledge becomes organized in efficient ways. This knowledge organization, in turn, changes the deal for the working memory. It changes it to this extent that Ericsson and Kintsch (1995) suggested the concept of *long-term working memory*. For instance, with increasing numerical skills, children do not have to memorize six digits separately, but can form two *chunks* of three digits each and thus increase their working memory capacity (Miller, 1956). With ongoing mathematical education, children can even solve mathematical problems described in text form. They quickly see the crucial cues that indicate which type of formula should be used. Based on this info, they know which other information they must search for in the text and which they can ignore to fill in the formula. Next, they solve the formula and formulate a solution to the problem. This procedure describes an exemplary use of a *schema* (Van Lehn, 1996). If a schema includes a specific temporal order, such as visiting a restaurant (enter a restaurant, look for a table, order from menu, …), it is called a *script* (Schank & Abelson, 1977). Another form of knowledge organization is forming *short-cuts* within long chains of reasoning by encapsulating parts of it into entities that are only unfolded into its pieces if necessary (Boshuizen & Schmidt, 1992; Schmidt & Boshuizen, 1992).

All these concepts not only describe efficient ways to *store* information in long-term memory, but also how this *expands* working memory: one entire chunk, schema, or script functions as only one entity. Thus, plenty capacity is left to collect new information to fill in the schema’s or script’s empty slots. Hence, these efficient ways of organizing knowledge, in turn, strongly guide search and intake of information (Jarodzka et al., 2017; Sheridan & Reingold, 2017). This guided processing of visual information, which assumes a constant interplay of cognitive and perceptual processes, is referred to as *visual expertise* or professional vision (Goodwin, 1994; Jarodzka et al., 2017; Sheridan & Reingold, 2017; Van Es & Sherin, 2002). This aspect of expertise runs so deep, that it can be even confirmed on the level of which brain regions are activated (Gauthier et al., 2000). For certain professions, such as radiology or chess, we already know a lot about this interplay (Gegenfurtner et al., 2011; Reingold et al., 2001; Sheridan & Reingold, 2017). In general, we can state that

Visual expertise encompasses the ability to search for efficiently and actively and to appropriately interpret relevant information.

Visual Expertise in Different Professions

Most of the research on visual expertise has used static stimuli. This is entirely valid for chess or radiology as these stimuli are static but does not make sense for many other domains where the task is inherently dynamic. In the following, I will discuss how eye tracking helped us to understand visual expertise in professions with inherently dynamic stimuli.

In the probably first study on this topic, we studied how expert *marine zoologists* and university students examined video recordings of fish swimming to classify their locomotion patterns (Jarodzka, Scheiter, et al., 2010). We analyzed that this task requires a three-step approach: namely, identifying those elements, which move in a relevant way (here: by contributing to forming thrust in contrast to passive movement due to water current) and interpreting how exactly those elements move. Both steps are inherently coupled to the dynamic visual input. Only after that, these observations can be assigned to the according technical term of locomotion pattern. Obviously, experts were more correct in the latter step. But eye tracking – in combination with protocols of thinking aloud – showed that experts indeed were more efficient in searching and interpreting the relevant information. Apart from that, they used knowledge-based shortcuts and the group overall displayed different approaches to this task. In another study we investigated visual expertise *in air traffic control* (Van Meeuwen et al., 2014). People working as our traffic controllers must constantly monitor dynamic radar screens. Their task is to chunk planes into groups, decide on the order in which these chunks may enter the airport, and finally steer the planes to the landing position. They must do so in a safe, efficient, and environmentally aware way. We compared how air traffic control students, beginning at traffic controllers, and experienced air traffic controllers executed this task while we eye tracked them. Results showed that with increasing expertise participants came up with better solutions and quicker time and their solutions become more similar. The amount of mental effort experience while performing this task was not linear though. While beginners experienced quite high levels of mental effort, experienced air traffic controls and students experienced low levels of mental effort. Moreover, we found that these three groups applied different visual strategies. First, with higher level of expertise air traffic controllers displayed more holistic processing of their radar screens as indicated by looking quicker to relevant areas and transitioning less between different elements. Experts visual processing was also more efficient in that they looked longer on relevant areas than students. Interestingly, beginners were sometimes even less efficient than students in their visual processing were. Finally, with increasing expertise individuals displayed more sophisticated task specific approaches to this task.

Visual Expertise in Medicine

Another profession, where visual expertise plays a key role is medicine (Jarodzka, Jaarsma, et al., 2015; Jarodzka & Boshuizen, 2017). In a literature review (Van der Gijp et al., 2017), we found that overall, individuals became faster in visually searching for suspicious areas in medical images with increasing expertise. Experts initially deploy a global impression of the entire image and follow this up with a detailed, focal search. Also, experts execute task-specific search patterns, such as drilling through CT-scans or systematic search on chest X-rays, more often than novices. In our first study on visual expertise in medicine (Balslev et al., 2012), we compared how *pediatric* experts diagnosed video recordings of infants suffering from epileptic seizures (or displaying behavior that is often mistaken for epilepsy) compared to medical students. We found that experts were not only more correct in diagnosing the behavior, but also looked quicker and longer at body parts relevant to the diagnosis. In a project on *pathology* (digital slides of colon tissue) we investigated how clinical pathologist, pathology residence, and medical students diagnose digitalized colon issue (Jaarsma et al., 2014, 2015, 2016). In doing so, we used diverse sets of data, namely diagnostic performance, zooming and panning movement in the digital colon slides, think aloud protocols, and eye tracking data. We found that experts use more *holistic* processing, as they spend more time on an overview of the slide and only zoom in on very specific locations. Also, with higher expertise individuals were able to provide correct diagnosis on very brief displays of the colon issue (Jaarsma et al., 2014). Interestingly, although expert and intermediate pathologists did not differ in their diagnostic performance, they did so in their individual processing of the colon tissue. While experts only quickly looked at the relevant areas and spent the remaining time checking for other (potentially) pathological abnormalities. Intermediates had to use all their time on re-checking diagnostically relevant areas, and they could have thus missed other abnormalities. Furthermore, pathologists with higher expertise had a more efficient approach to diagnosis through encapsulations and chunking in their verbalizations, but also by inspecting fewer diagnostically relevant areas visually. Finally, we found indications for task specific behavior, in that experts and intermediate show a clear orientation phase, intermediates also display a control phase at the end of the diagnostic process it, while novices show no uniform process at all. In the domain of *resuscitation* in an emergency room, we compared how medical professionals and medical students dealt with an emergency scenario in a simulation game (J. Y. Lee, Donkers, Jarodzka, & van Merriënboer, 2019). We compared them on their game-logs, eye tracking data, and subjective mental effort ratings. Results showed that experts performed better, were more systematic in their approach to the task, they were also more accurate in their motoric reaction and more efficient in their visual search for relevant information while experiencing less mental effort at the same time compared to novices. In a real-life situation within an emergency room, this scenario would be far more complex, as it would require the medical specialist to interact with the patient, various apparatuses and other medical personal (something that could have been only simulated in our case), which in turn requires experts to have an excellent situation awareness of what is going on (Endsley, 2018; Jarodzka, Jaarsma, et al., 2015).

In medical professions, a lot of information is present in visual form, while experience influences how this visual information is processed.

Visual Expertise of Teachers

The last profession I would like to discuss, where visual expertise is crucial, is that of teachers' classroom management[10]. Managing a classroom is a key competence of expert teachers to enable pupils' learning (Berliner, 2001; Hattie, 2009). It involves creating and maintaining "…a learning environment conducive to the goals of instruction" (Brophy, 1988). Consequently, good classroom management leads to pupils' better learning (M. C. Wang et al., 1993). The foundation of classroom management is the ability to notice, meaningfully interpret, and automatically monitor valuable visual cues, that is, visual expertise (Berliner, 2001; Doyle, 1970; Feldon, 2007) – something that beginning teachers struggle with (Sabers et al., 1991; Sherin, 2007; Van Es & Sherin, 2002). A concept strongly related to visual expertise is teachers' *withitness* – the ability to maintain an ongoing awareness of what is happening in the classroom and the events taking place within it (Kounin, 1977). In a project, we have compared how beginning and experienced teachers perceived and interpreted video clips of different classroom situations (Wolff et al., 2015, 2016, 2017). Participants were asked to think out loud and to signal when they saw an event relevant for classroom management while their eye movements were tracked. Over the course of this project, we found that novices reported classroom events in a more descriptive manner and focused on the current ongoing events and problematic behavior. While experts focused more on the question whether students were learning and considered implications for future events. In terms of visual processing, we found that novices often did not even notice relevant events, that their visual attention was scattered and that they mainly focused on visually salient events. While experts focused more on relevant areas and monitored all students more evenly. In a follow-up project, we moved into real classrooms and investigated this issue in teachers-in-training, beginning, and experienced teachers while they were teaching their own classes. We used three data sources to study visual expertise in classroom management, namely, the teachers gave a subtle hand-signal during teaching, when they noticed an event relevant to classroom management, we tracked their eye movements with eye tracking glasses during teaching, we interviewed them after each lesson on these events (van Driel et al., 2022). We found that although all teacher groups noticed similar amounts and types of relevant classroom management events, teachers-in-

[10] This research field often uses the term 'professional vision' instead of 'visual expertise' (Goodwin, 1994)

training identified more situations in the interviews after the lessons, while beginning teachers identified more events during teaching with the hand-signal (Van Driel et al., 2021). Ensuing, we developed a coding schema for the interviews to analyze teachers' in-action and on-action cognitions of classroom management events (Van Driel et al., 2022). While this project is still ongoing, this overall research area is growing as two recent Special Issues (Jarodzka et al., 2021; Lachner et al., 2016a) and a recent literature review demonstrate (König et al., 2022).

> Visual expertise, as in noticing and meaningfully interpreting events relevant for managing a classroom, is the foundation for good teaching.

Characteristics of Visual Expertise

So, what can we say on visual expertise overall based on the above-described findings? We know, that visual expertise is *composed of* a perceptual and a cognitive component: It requires noticing (precursors of) specific events or elements and their appropriate interpretation (e.g., Jarodzka & Boshuizen, 2017; Sheridan & Reingold, 2017; Van Es & Sherin, 2002). We also know, the visual expertise *results in* increased situational awareness of the surrounding; referred to as withitness in teaching (Jarodzka, Jaarsma, et al., 2015; Wolff et al., 2021). We have also seen repeatedly that visual expertise enables a quick holistic processing of an image which is then followed by an efficient foveal search (e.g., Jaarsma et al., 2014, 2015; Litchfield & Donovan, 2016; Sheridan & Reingold, 2017; Van der Gijp et al., 2017). This in turn results in a more efficient processing of the image or the surrounding (e.g., Balslev et al., 2012; Sheridan & Reingold, 2017; Van Meeuwen et al., 2014). Another issue that has come up repeatedly is that visual expertise is highly *domain specific* and even *task specific* (e.g., Nodine & Krupinski, 1998; Shanteau, 2015; Sheridan & Reingold, 2017; Van der Gijp et al., 2017). That means that experts in a specific task or domain display very specific visual strategies that might vary in even slightly adapted tasks. Thus, also the accompanying eye tracking measures differ very much between tasks and domains and consequently experts may sometimes have longer and sometimes shorter fixations than novices (Van der Gijp et al., 2017). Finally, what we also see is that visual expertise develops gradually (e.g., Van Meeuwen et al., 2014) and under certain circumstances and for certain aspects nonlinearly (e.g., Jaarsma et al., 2014; Lesgold et al., 1988; Van Driel et al., 2021).

The diverse perceptual processes and the complex cognitive structures described at the beginning of this chapter are tightly entangled. Moreover, the complexity of the real-life tasks in the diverse professions lead to a task-specific character of both components. Hence, it is challenging to formulate one coherent theoretical model of visual expertise. Rather, each existing model focuses on one specific profession and even there on very specific aspects of it. For instance in the domain of medicine, the holistic model of medical image perception by Kundel and colleagues (2008) focusses on the perceptual processes taking place when diagnosing medical images. While our own model (Jarodzka, Boshuizen, et al., 2013) emphasizes the cognitive structures and processes active in working and in long-term memory during the diagnosis of medical images. In the teaching profession, we have proposed one very broad model on teaching, including teachers' knowledge, their teaching practices, their visual expertise, the situational context, etc. and how these all interact and shape each other (Lachner et al., 2016b). In another model, we focus on the cognitive structures ('classroom management scripts') and how they play out during the act of teaching (Wolff et al., 2021). What we still miss is a detailed model on the perceptual aspects of visual expertise in teaching and classroom management. However, it is very likely that the plenty of recent and ongoing research on this topic will enable such a model. In particular, as we see a shift of this research from artificial laboratory settings to real-life classrooms, and from studying only the perception of teachers towards more and more instruction and teacher-student interactions (Jarodzka et al., 2021).

Training Visual Expertise

On a final note, it is important to remember that the aim of expertise research is to draw conclusions on how to foster its development. Thanks to decades of expertise research (for an in-depth overview, see Ericsson et al., 2018), we know pretty well, what type of knowledge is acquired at each stage of expertise development, how this knowledge is acquired and organized, and how this can be supported (Table *3*).

Table 3

Development of Expertise

	Novice	**Intermediate**	**Expert**
Type of knowledge	Biomedical, Factual, Textbook	Clinical, Practical experience	Textbook knowledge embedded into practical experience, Pedagogical content knowledge
Acquired by	Studying textbooks	Applying biomedical knowledge to clinical practice, Encountering practice	Instantiating, Testing, Adapting
Knowledge organization	Networks	Knowledge encapsulation, Chunking	Illness-scrips, Schemata, Scripts
Instructional intervention	Optimally designed instructional material	Experiencing real-life cases	Deliberate practice

We know far less on how to train visual components of expertise, but there is sufficient evidence that eye tracking can provide valuable insights into this issue (Ashraf et al., 2018). Several approaches have been studied to train visual expertise, such as directly instructing students how to look (Grub et al., 2022; e.g., E. M. Kok et al., 2016), eye movement modeling examples (e.g., Emhardt et al., submitted; Gegenfurtner, Lehtinen, et al., 2017; Xie et al., 2021), by one-on-one master-apprentice instruction (Jaarsma et al., 2018), or by deliberate practice of the professional themself (Jarodzka, Jaarsma, et al., 2015). Several issues are noteworthy when it comes to such a training, though. First, it is pretty clear that teaching perceptual strategies in isolation, is not sufficient to develop visual expertise in a task (E. Kok et al., 2016; Van der Gijp et al., 2017). Second, a training of visual expertise must be embedded in such complex and realistic scenarios that they may become overwhelming for the learners. Hence, a conscious use of pauses, to either off-load mental burden or to actively reflect on the task, seems to be beneficial (J. Y. Lee et al., 2020, 2021). Finally, we cannot say today, how the workplace of tomorrow will look like and what specific visual expertise will be required from the professionals, and future research should focus more on how to solve this problem. We argue, that to achieve this a multitude of aspects must come together: the *organizational context* that embraces routines, but also provides room for development both for professionals, but also beginners, the *learning environment* that should be as authentic as possible, and the *learning activities* that encourage reflection and dialogue with a master (Duchatelet et al., n.d.).

Challenges

Eye tracking provides us with so many exciting chances to better understand and foster learning, to improve testing and to support professionalization. However, I do not want to oversell it as the bright solution to everything. In the following, I will address three challenges that we must be aware of when using eye tracking, but even if we read about eye tracking research, namely methodological limitations, conceptual challenges, and legal as well as ethical issues.

Methodological Limitations

Eye tracking data are vulnerable to biases on several stages of the experimental process. First, when *setting up an eye tracking experiment* it is crucial to avoid any possible biases or artefacts in the data recording. For instance, it is important to consider carefully the visual set-up of the stimulus – and of the control stimulus! Eye movements are very prone to different visual features, such as the brightness of the screen or the placement of the target. Moreover, other infrared light sources than the eye tracker itself should be excluded or kept stable, most often this is sunlight. But also, other distractions that would easily draw the visual attention from the task, such as a noisy hallway next to the recording room. Second, another key factor of high quality of the eye tracking data is operating the *hardware and the software*. Obviously, both hardware and software should match the research question, such as one should not try to detect detailed differences with an eye tracker that has only low-resolution. Similarly, one should not expect participants to behave naturally in an artificial laboratory setting with a bite-bar or chinrest attached to the eye tracker. An easily overlooked factor here is the experimenter themself. To ensure reliable and valid data the hardware and software must be handled with utmost care. An inexperienced or careless experimenter can mess up an entire data set, for instance, by not caring enough for the calibration or not observing the quality of the eye detection throughout the entire recording session. These issues might be very difficult to detect afterwards. Third, we must be very aware of further *post-processing and analyzing* of the data. In contrast to many other data types, the difficult decisions already start with the first processing steps when detecting eye movements within streams of raw data, which will lead to overestimating or underestimating certain eye movement events. Moreover, defining which concrete areas of the stimulus will be of interest for further analysis and where their boundaries lie will have very concrete and strong influences on the results you get from these data sets. Finally, the statistical testing is a challenge: eye tracking data are often not normally distributed and thus require appropriate statistical handling. On the other hand, eye tracking data require serious investment into data collection, both from the researcher (each participant must be recorded separately with sufficient preparation time) but also from the participants. It boils down to the question of what kind of research do we want to conduct in educational sciences. When conducting a power analysis, the number of participants required is oftentimes quite high. However, these tests were developed with questionnaire research in mind. Can we expect to bother that many school kids or students and take away their lesson time for research? Or should we rather conduct exploratory, descriptive research in the first place?

Several books and articles provide in-depth information on these topics (Duchowski, 2003; Gegenfurtner, Kok, et al., 2017; Holmqvist et al., 2011; E. M. Kok & Jarodzka, 2017a). Ultimately, however, the researcher themself must carefully consider each of these steps and make an informed decision. Their decisions will likely never be undisputed, making it all the more important to report and justify each of them when reporting eye tracking studies (Holmqvist et al., 2022).

Conceptual Challenges

Eye trackers measure *where* a person looked at, for how long and in which order. Full stop. That's it. Everything beyond this statement is an interpretation of the data with uncertainties and we seriously need to be cautious with any broader interpretations (Gegenfurtner, Kok, et al., 2017; E. M. Kok & Jarodzka, 2017a, 2017b). However, we do want to draw further meaningful conclusions and not just stick to reporting plain measures. Hence, we need to take certain precautions. For instance, what is often done is a *methodological triangulation* of eye tracking data with other sorts of data such as verbal reports, performance data, logging data, etc. (Holmqvist et al., 2011; Jarodzka, 2021). Also, we need to embed the entire research process into existing theories: from formulating the research questions, to designing the experiments up to interpreting the research findings (E. M. Kok & Jarodzka, 2017a, 2017b). Finally, it is always advisable to have a close look into already existing research and well-established research paradigms (Liversedge et al., 2011). These provide interesting ideas, on how to proceed with setting up experiments and subsequently interpreting the data.

Privacy, Ethics, and Legal Issues

As researchers, we often focus on the chances of a new methodology and by this enthusiasm, we may overlook its threats. This is also the case for eye tracking research. In 2018, I addressed this topic in a keynote at a major eye tracking conference when talking about the usage of eye tracking in educational science (https://etra.acm.org/2018/keynotes.html https://www.blickshift.com/highlights-of-etra-2018/). The year after this topic was picked up as a panel discussion (https://etra.acm.org/2019/panel.html) and over the past two years, a workshop was organized on this topic (https://prethics.cispa.saarland/ https://prethics.perceptualui.org/). Hence, the interest is rightfully growing, albeit still being a niche at eye tracking conferences. My goal is to convince you with this section that we must consider privacy, ethics, and legal issues far more when dealing with eye tracking. In the following, I describe, why the topic of privacy, ethics, and legal issues are relevant for eye tracking, what threats come from this for participants and educational practice, but also which threats occur for research in educational sciences with eye tracking.

Eye Tracking From a Legal Perspective

As European citizens, the most important law when it comes to privacy issues, is the *General Data Protection Act (GDPR)* § 89 (33). This law protects us from others collecting data on our ethnicity, religious beliefs, sexual orientation, health state, political opinions etc. However, exceptions are possible. If we want to conduct scientific research and therefore collect personal data, we must gain informed consent from those we collect this data from and process it with utmost care. We now need to break down this statement. First, we need to establish, whether eye tracking is personal data. *Personal data* is "any information which are related to an identified or identifiable natural person." §4(1) (https://gdpr-info.eu/issues/personal-data/). Unless we do not store recordings under the actual names of participants, but under anonymized codes, a person cannot be *directly* identified from eye tracking data. However, eye tracking data are very rich data sets (between 30 and 1000 Hz of binocular x- & y-coordinates, plus pupil dilation) and some eye movements features seem to be idiosyncratic (e.g., Andrews & Coppola, 1999). Knowing what Big Data algorithms are already capable of we must assume that it is (or soon will be) possible to identify a person from raw eye tracking data *indirectly.* We can even go one step further and argue that eye tracking is a specific form of personal data, namely biomedical data (i.e., the technical processing of physical, physiological, or behavioral data). This issue used to be even more severe in earlier generations of high-resolution eye trackers stored detailed, close-up video recordings of the participants' eyes. This is not the case anymore in current eye tracking devices. However, there are two scenarios, where we must think beyond the mere raw data text files from the participants, namely webcam-based and mobile eye tracking. Webcam-based eye tracking uses the video recording of a participant's personal laptop to detect their eyes and how these eyes move. A video recording of someone's face is a *directly* identifiable personal data, thereby, posing a higher threat to the participant. Mobile eye tracking is not an increased threat to the participant themself, but rather to everyone else interacting with them. The mobile eye tracker records a video of where the participant is looking at, which may be another person. Hence, depending on where this person is located at the time of the recording (private vs public space), they also need to provide consent or at least be informed about the ongoing recording.

Having established that eye tracking data is personal data, we need to gain *consent* (§7) from those, we want to eye track. This consent needs to be active and is ideally given in written form. Consent can be withdrawn for as long as this is technically possible. Meaning, once the data is fully anonymized, a specific person's data cannot be mapped anymore and hence, cannot be deleted from the entire data set. In educational sciences we often deal with minors, in which case, also the parents need to (actively) consent to a data recording of eye tracking (i.e., personal) data. Finally, *processing* of personal data includes all stages of eye tracking research, namely recording, storing, and analyzing. Hence, we need to adhere to necessary precautions for personal data on all stages of our research. Meaning that we need to be aware, who has access to the eye tracker itself, but also with whom and how we share our data for analyses.

It is important to remember that on top of the GDPR, also national legislations may apply.

Eye tracking data are personal data that must be processed with appropriate care and upon informed consent.

Threats From Eye Tracking

Eye tracking is constantly becoming cheaper and less obtrusive. We can eye track people with regular web cameras (e.g., https://gazerecorder.com/), we can purchase an eye tracker on Amazon for less than 260 euros and get it delivered by tomorrow. Big tech companies have purchased or invested into eye tracking over the past couple of years, such as Microsoft, Google, Facebook, Apple, etc. Also, we see more and more eye trackers in our everyday devices, such as cars, laptops, navigating through train stations or even when ordering pizza (https://blog.pizzahut.com/order-a-pizza-with-your-eyeballs/). Hence, it is safe to say that eye trackers collecting our personal data are coming our way. But how big is the threat? What can they reveal about us?

The problem is twofold: first, we move our eyes subconsciously and still these eye movements can potentially reveal a lot about us. Kröger, Lutz and Müller (2020) made a detailed analyses of which data exactly can be captured with eye trackers and what these data can potentially reveal about a person, ranging from demographics (age, gender, geographical origin), to states (mental effort, cognitive processing, fatigue, mood), to personal traits (e.g., neuroticism, abilities and skills), and even health information (physical health, mental health, drug use). Do we really want to share this much information and if so, under which circumstances and when? What is also concerning is the thought that I presented in the first section of this chapter (pp. 55), namely that we cannot be entirely sure what we do get out of eye tracking data. Hence, we might assume someone's private information, because an algorithm told us that this is most likely, but we still can be wrong in this individual case. Second, the fact that commercial parties are increasingly gaining access to eye tracking data their possibilities are unforeseeable in combination with artificial intelligence (AI). Who decides, which of this information may be tracked and who gets when access to this information? At all cost, we must avoid a dystopian future as envisioned by Dave Eggers in his novel 'The Circle' (2013), in which an all-encompassing social media company imposes the following mission statement upon all its members "Secrets are lies. Sharing is caring. Privacy is theft.".

Threats for Research

As much as I am concerned about what commercial parties can do with eye tracking to consumers, who do not understand what they are sharing, I am also concerned for unintended consequences for research, for eye tracking research in educational sciences specifically. The biggest risk stemming from regulations described above (p. 57) to educational research in classroom settings (e.g., p. 50). Such ecologically valid research with mobile eye tracking, suffers tremendously under the GDPR. When conducting mobile eye tracking of the teacher in a classroom full of pupils, it means that to record one participant, you need the active informed consent of the teacher themself, but also from each pupil and their parents (if the pupils are minors) as the mobile eye tracker records videos of them. As many colleagues have confirmed, it is almost impossible to obtain written consent of all students and their parents to obtain the recording of only one teacher. The situation becomes even more difficult, if you try to record mobile eye tracking data on the street. It is almost not feasible anymore to conduct such research (Jarodzka et al., 2021).

Another big problem is that, as researchers, we are obliged to several (national) regulations of *good scientific practice*. In the Netherlands (and for Educational Sciences), these are the 'Wet op hoger onderwijs and wetenschappelijk onderzoek (WHW)' §1.7, the Netherlands Code of Conduct for Research Integrity (2018), the Ethical Code of the National Ethics Council for Social and Behavioural Sciences in the Netherlands, and the guidelines of the American Psychological Association (APA). Unfortunately, these regulations are in stark contrast to the GDPR requirements. For instance, in terms of scientific integrity, we are obliged to store data sets for a prolonged time (10 years) to avoid fabrication or falsification of data. Moreover, recent developments on ethics in scientific research require to share data with other researchers and preferably even with the broad public in the spirit of Open Science (https://www.universiteitenvannederland.nl/open-science.html). Having established that eye tracking data are personal data, that have the potential to reveal extremely intimate information about the participants, and in the case of mobile eye tracking, even of third persons, this is simply not possible.

Eye tracking data hold high promises, but also present serious threats to privacy and ethics, which in turn, endanger feasibility of ecological research and the spirit of open science.

CONCLUSIONS

So, was Thomas Aquinas correct with his statement that our mind is filled with thoughts we base on what we see, hear or perceive otherwise? This is a rather philosophical question, but we cannot deny how much our thoughts are influenced by what we perceive. Does this also mean that once we see (or perceive otherwise), we do learn? Certainly not, but it means that seeing is one of the key channels through which most of us perceive and hence, a *prerequisite* of learning.

Eye tracking as a method to measure seeing can reveal different processes underlying learning and testing, such as searching, organizing, and integrating information, the amount of effort imposed, but also different strategies people apply to study learning or testing material. This can help us to better understand human information processing and thus to improve and develop existing theoretical models. This knowledge can also help us to develop guidelines on how to design efficient learning and valid testing material for digital online education. Furthermore, with the help of eye tracking we can better understand how professionals deal with complex, information-rich environments and how we can train others on the route to expertise. To ensure that eye tracking research in educational science stays relevant, we must stay as close as possible to 'the wild' of educational practice and be prepared for serendipity findings, such as that what we found in a well-controlled laboratory experiment about how people visually process information and how they learn, might be different from when they sit in a classroom filled with other students (Oliva et al., 2017; Skuballa et al., 2019).

When diving into educational practice, though, we must consider ethical issues of eye tracking. This does not only include adhering to the law, but also asking ourselves how much insight we want our teachers to have into our students' minds. To make an informed statement on that, we must investigate which benefits and innovations eye tracking can bring into our educational practice. From the students' perspective, for instance, looking through the eyes of the teacher explaining complex theoretical models in online video lectures (Emhardt et al., 2022). From the teachers' perspective, they can use their students' visual processes as clues for their learning progress (E. M. Kok et al., subm., in prep). And teachers can use eye tracking even directly as training interventions (https://www.lesediagnostik.de/) or as a basis for interactions with a digital learning environment (Duchowski, 2018; Scheiter et al., 2019).

For a responsible usage of eye tracking in educational practice, the question is not if, but rather how, when and under which circumstances should we allow it to get the most benefits with the least threats.

Acknowledgements

They say it takes a village to raise a child – imagine how many it takes to make someone a professor! So many people have contributed directly and indirectly to my journey on the way to a scientific career that it is impossible to mention them all, yet I would like to thank some of them personally:

First of all, I would like to thank the Executive Board of the Open Universiteit and especially our Rector Magnificus Theo Bastiaens for appointing me Professor of Online Learning and Instructional Design at the Open Universiteit. I am much honored to accept this title and I am grateful for the trust they place in me. In addition, I would like to express my gratitude to our former Dean Saskia Brand-Gruwel and to our former interim Chair Wim Jochems. Both of them have put their faith in me and personally engaged to ensure that I received this position as of September 2019. I would also like to thank our current dean, Desirée Joosten-ten Brinke, for being instrumental in supporting me in this position and for encouraging my continuous growth in the role as chair of the department Online Learning and Instruction (OLI). But also the current management team under her leadership, namely our Research Director Rob Martens, our Teaching Director José Janssen, and the head of our Support Office Marion Timmermans as well as my colleague department chairs, namely Renate de Groot, Karel Kreijns, and Roland Klemke.

Next, I would like to thank those, who mentored me during my time at the Open Universiteit starting in June 2010. It all started when Paul Kirschner entered my scientific life and brought me to the Open Universiteit. He trusted me and supported me in difficult times, guided me wherever necessary, but never pushed me in any direction. He provided me with everything needed to flourish, and to this day always has sage advice whenever I get stuck. It was also around this time that I met Els Boshuizen, whom I secretly admired from afar for her groundbreaking work on expertise. I immediately wanted to work with her, and she gave me key opportunities to do so. Most importantly, she broadened my horizons about how to think about and conduct research. She inspired me as a researcher and as a person, and she continues to do so to this day. Renate de Groot, who started at this university at the same time as I did, taught me a lot about how to build a research line and lead a research group, but also about how to be a mother while pursuing an academic career. Her example gave me the courage to try to do both, her active

support and commitment as my department chair have been instrumental in me becoming a full professor and department chair myself, and I continue to learn from her and lean on her along the way. Saskia Brand-Gruwel was another incredibly inspiring researcher, and her work on students' critical thinking and digital skills is very relevant to our society today. I gladly worked with her to build a line of research that I thought would have so many interesting possibilities. It was therefore a shock to me when I learned that she was leaving the Open Universiteit – but she did not do so until she had helped me reach my current position, to find a new journey for myself.

This journey has been going on for almost three years now and it is joint by the best research team I could ever have wished for! And even if some of them have taken a different path in the meantime, each of them contributed or is still contributing to the success of our OLI department in their own way: Gino Camp, José Janssen, Hendrik Drachsler, Kevin Ackermans, Leen Catrysse, Dorothy Duchatelet, Konstantinos Georgiadis, Tamara Schleepen and the former members: Kim Dirkx, Yvonne Kammerer, Ellen Kok, and Irene Skuballa. However, as important as senior researchers are, the true backbone of any research is the Ph.D. candidates who bring the vague research ideas to life, shape them, and eventually become experts in their own right in their respective fields. The ideas in this book are based on their hard work, their sometimes crazy ideas, their great fun, and their always contagious enthusiasm. I have learned so much form each of them and hope to continue to work with as many of them as possible. Not only do I believe that they all have the potential to make crucial contributions to our field of research, but each and every one of them is a great person with whom I tremendously have enjoyed working. They are: Thomas Jaarsma, Charlotte Wolff, Manuel Oliva, Jaap Walhout, Tim van Marlen, Michelle Nugteren, Bibeg Limbu, Sharisse van Driel, Selina Ermhardt, Sterre Ruitenburg, and Andrienne Kerckhoffs. And, of course, I am indebted to Danielle Amendt, not only for her help in organizing all the formalities related to my inaugural lecture, but also for her daily support of OLI.

Apart from the Open Universiteit, I am fortunate to have a wide network of truly inspiring researchers around the world to collaborate with and learn from. It is not possible to name every single one of them, but I wholeheartedly appreciate each one of these past and ongoing collaborations. Still, I would like to mention the most influential of them.

I begin with Tamara van Gog, who has been a true role model for me as a researcher since I met her in the early stages of my Ph.D. I was incredibly lucky that she cooperated with me right away, and I owe important achievements in my career to her. Not only is she one of the brightest minds and most successful researchers in our field, but she is also so, so much fun! I am proud that she turned into a friend and into family by becoming the godmother of my first daughter (because she simply rocks, and I want my daughters to have such a great woman in their lives to look up to!). Another researcher who became a friend and shaped my career and research interest is Kenneth Holmqvist. He not only taught me so much about eye tracking, but also about how to create a calm, unagitated, and constructive research environment that has drawn me back to his lab at Lund University for years. There, I met and collaborated with other remarkable eye tracking researchers, such as Marcus Nyström or Dee Niehorster – with whom I still work today. Next is Hans Gruber from the University of Regensburg, who mentored me in the past years and to whom I owe some big steps in my career, such as the joint initiation of a new a Special Interest Group for online measures of learning processes at the European Association of Research on Learning and Instruction (together with Paul Kirschner). I also had the opportunity to work with and learn from Jeroen van Merriënboer from Maastricht University, who took me on board to supervise joint Ph.D. projects and always has good advice when I have doubts. I must say that every conversation with one of the people mentioned here is an opportunity to learn something – be it about research, management or just life itself. Even though it has been a while since I have actively worked with them, I would like to conclude by thanking those researchers who sparked my interest in research and gave me a head start at the Leibniz Institute on Knowledge Media in Tübingen: Ulrike Cress, the current director of this institute, infected me with her enthusiasm for research by taking me to my very first conference, sharing many deets on a research career, introducing me to her network at SAP (where I met my future husband!), and supervising my diploma thesis. I went on to do my doctorate at the same institute under the supervision of Peter Gerjets and Katharina Scheiter, who solidified my decision to pursue an academic career. Not only did I learn so much from them about the entire research process, but they also introduced me to their research network, from which I still benefit, and they gave me all the freedom I needed to pursue my own interests, while keeping me on track towards the goal of improving learning and instruction.

So, when you see how many great minds I have been privileged to work with and have received so much support from, you realize that only half of this journey is hard work, but the other half is the luck of working with such people – and for that I am immensely grateful. Yet again, that is only part of the story, because without friends and family to lean on, you cannot be successful in your career.

I am fortunate to have a large family, and although we live far apart and see each other too rarely, every moment with them fills me with so much joy and fuels me with energy to keep going on – even when they are no longer with us. That said, I have to acknowledge a few of them personally, as they directly contributed to my ability to pursue this career over the past years. First of all, my mother. I am forever in her debt for fighting for a better future for us, and without her strength and diligence, I would not be where I am today. Considering where we started, it is to her personal credit that I am who I am against all odds. She shaped me and she continues to do so. I am also incredibly fortunate to have a loving and caring mother-in-law who supported me both in pursuing a scientific career and in being a mother. I can wholeheartedly say that her support has directly contributed to me achieving this step in my career. I am probably most indebted to my two daughters, Matylda and Irmina. They keep up with me no matter what, and have all the understanding and love that such young children could possibly give. They make the 'life' in 'work-life-balance' intense yet so fulfilling. They literately give my life meaning. Whatever you two become in life, be it astronauts, mermaids, paleontologists, or unicorns, may you become happy first and foremost. Last but not least, Christian. Annie Lennox and Aretha Franklin once sang: "Sisters are doin' it for themselves!". And while I admire them both, I could not agree less with this sentiment. Without him and his unconditional love and support, I could not be where I am now. Neither career-wise nor family-wise. The fact that we both pursue full-time careers and have children while living far away from our families is only possible because we both get equally involved – and we both win. He is a true feminist and there is no other that I would rather be with on this crazy journey called life!

Ik heb gezegd.

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ISBN 978 94 6469 074 3

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