How to measure attention?

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Researchers who are interested in attention generally have one or more of the following goals: 1) to identify sources of information in the environment that are selected and prioritized by the observer, 2) to quantify the effect of attention on task performance, and 3) to identify neural correlates of attention. When considering methods to measure attention, it is important to distinguish between overt and covert orienting mechanisms. Overt attention is expressed by movements of the body and can be measured directly by determining the position and velocity of the relevant effectors – primarily the eyes, head, and hands. Covert orienting refers to the ability to direct attention without body movement, and is primarily measured by differences in task performance (e.g. reaction time) that cannot be attributed to changes in the external stimulus.

In this chapter we will focus on quantitative techniques that provide fine-grain spatial and temporal information about attentive responses at a macro scale. We do not discuss the many psychophysical paradigms that have been used to infer attention based on the speed and accuracy of observer judgments. Micro measurements of single neuron or several neurons using micro-electrodes are not described here. However, in the chapter "Effects of Attention in Visual Cortex: Linking Single Neuron Physiology to Visual Detection and Discrimination", the use of micro-electrodes to measure single neuron responses is described.

At a macro scale, the attentive response can be either measured directly in the brain, or indirectly through participants' behavior. Only one of the techniques that is described here is based on participant active feedback: mouse tracking. This is because the mouse tracking feedback is very close to eye-tracking and this is an emerging approach of interest for the future: it requires less time, less money and provides more data than classical eye-tracking. All the other methods are direct or indirect and provide objective measures of attention. In a first part the indirect methods are described while direct methods are mainly dealt with in a second stage.

1. Indirect measures of attention

Eye-tracking: a gold standard for overt attention

If “the eyes are windows to the soul”, eye-tracking consists of taking a look to it. Indeed, eye-tracking is probably the most widely used tool for measuring visual attention. Although attention can be directed without moving the eyes, it is generally the case that humans look where they attend and vice-versa. There is ample neurophysiological support for this proposition as several structures that are involved in attention – in prefrontal cortex, parietal cortex, and the midbrain – are also involved in guiding voluntary eye movements.

Eye trackers are devices that determine the orientation of the eye relative to the head (eye-in-head) or to an external frame of reference (eye-in-space.) If head position is known, then the orbital position of the eye (eye-in-head) is sufficient to determine gaze direction (eye-in-space.)

Eye-tracking technology has evolved over time. Different technologies are described in [1]. One of the earliest techniques to be widely used is EOG (Electro-OculoGraphy). The eye itself generates an electric dipole oriented along the corneo-retinal axis. This potential can be measured by placing electrodes on the skin around the eye. From these electrodes, the eye orientation relative to the head can be reconstructed. To determine the orientation of the eye in space, the head must either be attached to a fixed system (chin rest or bite bar) or a head tracking system must be used in addition to the EOG. EOG signals are noisy and confounded by skin conductance or the activity of facial muscles. Reliable measurements typically require averaging over trials.

A more precise method was developed in the 1960s [2][3] using the scleral search coil. Here, a loop of wire is embedded in an annular contact lens placed around the cornea. A small electric current is passed through the wire, generating a magnetic dipole whose orientation moves with the eye. The subject sits with their head inside an oscillating magnetic field generated by a pair of large (roughly 2-3 feet in diameter) field coils. Electronics are used to sense the orientation of the scleral coil and hence the orientation of the eye. This system measures eye orientation relative to the field coils, which are fixed in space. The head generally needs to be stabilized to avoid confusing the rotation of the eye with translations due to head movement. A separate head coil can be used to record head movement. Binocular search coil systems allow experimenters to reconstruct vergence angle. Torsional eye movements can also be recorded. Scleral search coil systems provide continuous temporal resolution, limited only by front end filtering and the sampling rate of the recording device use to convert the analog signal to digital samples. Spatial resolution is typically 0.1 deg of visual angle or better and noise is extremely low. Contact lens search coils can only be worn for a short time (<30 min) as they cause an increase in intraocular pressure during the time that they are in contact with the sclera. This method should be used only under the supervision of a trained clinical ophthalmologist.

The technique that most of the current commercial and research solutions use is Video OculoGraphy (VOG), based on a video camera to detect the pupil and corneal reflection. An infrared light source illuminates the eyes. The light is either reflected (bright pupil) or absorbed (dark pupil) by the pupil and image processing software (usually embedded in dedicated hardware) is used to detect the edges of the pupil either by filling in or fitting an ellipse to the edge of the iris (Figure 1). This processing also provides an estimate of pupil size. Crosshairs identify the horizontal and vertical position of the center of the pupil. Some light is also reflected from the cornea and is called the corneal reflection (CR). The position of the pupil and corneal reflection is sensitive to head movement. However, the difference (pupil – CR) discounts the influence of head motion and gives a robust estimate of eye orientation in space. Nevertheless, for precise measurements, it is best to stabilize the head with a chin-rest or bite-bar.

It must be kept in mind that VOG trackers operate on a two-dimensional image of the eye. To obtain eye orientation, the appropriate transformation must be done considering the geometry of the camera relative to the eye, and the projection of a 3D sphere on to a 2D image. Alternatively, a look-up table matching eye position to tracker output can be generated by having subjects fixate on targets at known positions. A grid of at least 9 positions should be used for this calibration. VOG systems work best when the optics of the camera are aligned with the optical axis of the eye when the subject is looking straight ahead (primary position). An infrared or “hot” mirror placed in front of the eye can be used to achieve this alignment. The infrared mirror is transparent to visible light. This way, the subject can directly view the visual display or scene through the mirror, while the camera is placed off to the side.

The temporal resolution of VOG systems is limited by the framerate of the camera and the speed of the image processing algorithm that identifies the pupil and corneal reflection. Commercially available systems range from 30 Hz to over 1000 Hz. Spatial resolution is limited by the resolution of the camera. Typically, this is enhanced by using telephoto and close-up lenses to magnify the image of the eye. Many systems provide spatial resolution comparable to search coils (0.1 deg of visual angle or less). Drawbacks of VOG systems include sensitivity to stray light, which may cause large apparent changes in eye position. Furthermore, these systems are unable to function when the subject blinks, and typically set their output to a default value whenever this happens.

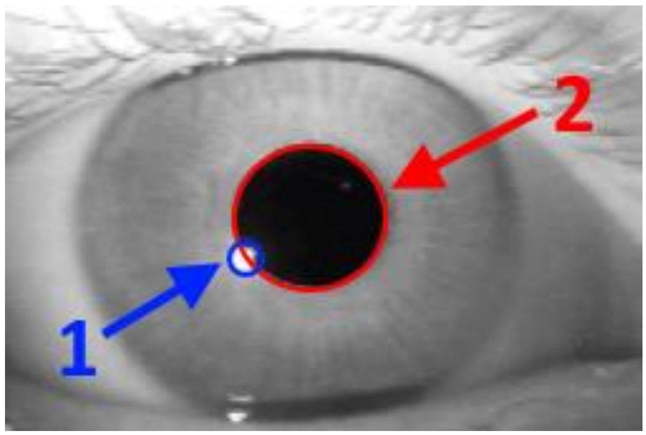

Fig1: The relative position of the pupil (arrow 2) and the corneal reflection (arrow1) are used to compute the gaze direction.

While the fundamental technique is most of the time the same, the embodiment of the eye-tracker can be very different. The main eye-tracking manufacturers propose the system under different forms [4][5][6].

Fig 2: Example of eye-tracking device included in a high resolution screen (here a Tobii system).

Some eye-trackers are directly incorporated into the screen (Figure 2) which is used to present the data. This setup has the advantage of a very short calibration, but it can only be used with its own screen.

Separate cameras need some additional calibration time but the tests can be done on any screen and even in real scenes by using a scene camera to which the system needs to be calibrated (Figure 3).

Fig 3: Binocular eye-tracking system independent from the screen (here a Facelab system).

The eye-tracking glasses (Figure 4) can be used in a very ecological setup, even outside on real-life scenes. An issue of those systems is that it is not easy to aggregate the data from several viewers as the scene which is viewed is not the same. The aggregation needs a non-trivial registration of the scenes which might need to install markers before the experiment.

Fig 4: Eye-tracking embedded in wireless (here a SMI system).

Cheap devices (Figure 5) are beginning to appear and quite precise cameras are sold less than 100 EUR [7] which is a fraction of the price of a professional eye-tracker. An issue with these eye-trackers is that they are packaged with minimal software and it is often difficult to synchronize the stimuli and the related eye movement data. These eye-trackers are mostly used as real-time human-machine interaction devices in gaming applications. Nevertheless, there are open source projects which allow recording of data from low cost eye-trackers like Ogama [8], but mainly on still images and not moving stimuli.

Fig 5: Low-cost eye-tracking device here attached to a tablet (here the Eye-tribe system).

Finally, webcam-based software is freely available [9]. They are able to provide good quality data and to be used remotely with existing webcams [10].

Eye movement behavior has a rich variety of features that are indicative of attention. In primates, voluntary eye movements consist of saccades (rapid changes in position with peak velocity >> 100 deg/sec), vergence (changes in the alignment of the two eyes), and smooth pursuit (slow movements, generally under 100 deg/sec, that track small moving targets). Between these movements are periods of fixation, though microscopic movements (drift, tremor, and microsaccades) may still occur even when the eye is relatively still. Fixations can be detected using clustering algorithms [11] or simply by using a double threshold: a time threshold and a spatial threshold to be sure that the gaze focused a small region. Fixation duration can be a measure of attention [12]. Fixations and intervening movements can be used to generate scanpaths (Figure 6) or heatmaps (Figure 7). A heatmap is a low-pass filtered accumulation of scan paths and it indicates the average attention attraction of each pixel. Usually for a result to be significant there is a need of a minimum of 10 participants per stimulus.

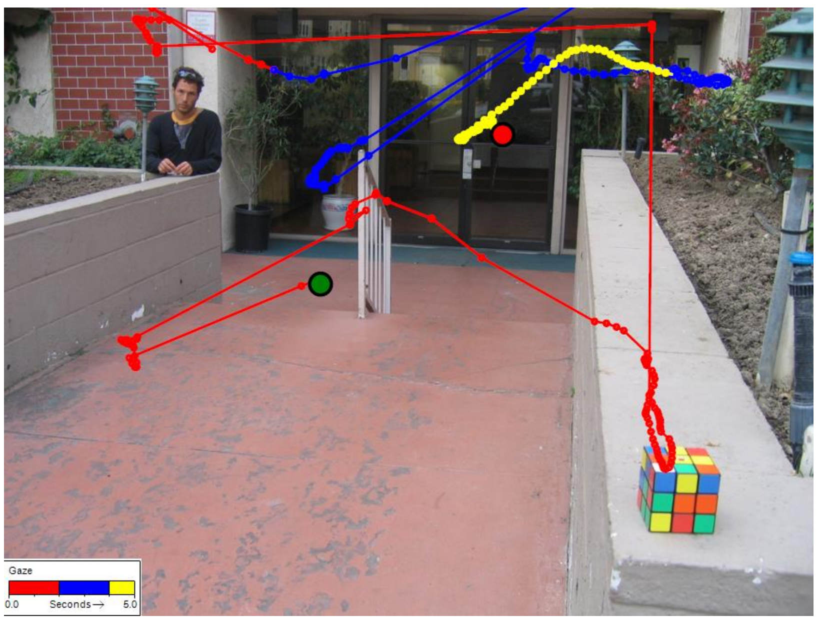

Fig 6: Example of eye scan path provided by eye-tracking systems

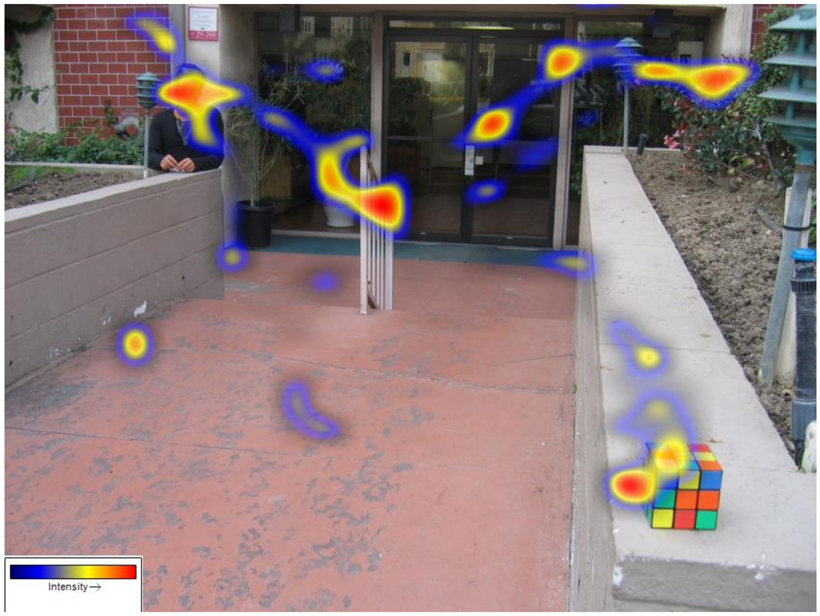

Fig 7: Example of attention heatmap averaged over the participants

During fixations, subjects often make very small eye movements called microsaccades [13]. These are saccades with amplitudes of less than 2 degrees of visual angle. Spontaneous microsaccades are often correlated with attention [14].

When viewing static scenes at a fixed depth, the most common eye movements are saccades, which normally occur roughly 2-3 times per second. The onset of a saccade can be detected to within a few milliseconds using algorithms based on eye velocity or acceleration. The latency of saccades relative to the sudden appearance of a target is generally 150-300 msec. Variations in saccade latency may be related to attention [15]. Attention may alter saccade direction [16], or may result in curved saccade trajectories [17].

Mouse-tracking: the low-cost eye-tracking

If eye tracking is the most reliable ground truth in the study of overt visual attention, it has several drawbacks in addition to the high cost of the professional devices:

- it needs minimal practice for the operator
- the user head might need to be stabilized
- the calibration process might be long

- the infrared light pointing the eyes might induce eye fatigue especially during long tests
- the system might work much less well depending on the user eye color or if he wears glasses

A much simpler way to acquire data about visual attention may be the use of mouse tracking. The mouse can be precisely followed while an Internet browser is open by using a client-side language like JavaScript. The mouse precise position on the screen can be either captured using homemade code or existing libraries like [18][19]. This technique may appear as not very reliable; however, its accuracy depends on the context of the experiment.

The first case is the one where the participant is unaware of the fact that the mouse motion is recorded. In this case mouse motion is not accurate enough. Indeed there is no automatic following of the eye gaze by the hand even if a tendency of the hand (and consequently the mouse) to follow the gaze is visible. Sometimes the mouse is only used to scroll a page and the eyes are very far from the mouse pointer for example.
The second case is the one where the participant is aware of the experiment and has a task to follow. This can go from a simple “point the mouse where you look” instruction as in [20] where mouse tracking was used for the first time for saliency evaluation to more recent approaches as the one of SALICON in [21] where multi-resolution interactive cursor mimicking the fovea resolution is used to encourage people to point the mouse curser where they look. Indeed, as the image resolution is decreased far from the cursor, people tend to point at the locations they are interested in to have a full-resolution view of those regions.
In this second case where the participant is aware about his mouse motion tracking, the results of mouse tracking are very close to eye tracking as shown by Egner and Scheier (Figure 8) on their website [22]. However, small or unconscious eye movements may be missed.

The main advantages of mouse tracking are low price and the complete transparency for the users (they just move a mouse pointer). The output can be the same as in eye-tracking. It can either be a heatmap (Figure 9), but also scan paths, raw data, etc.

Fig 8: Eye-tracking and mouse-tracking correlation. Adapted from [13]

Fig 9: Left: initial presented image, Right: mouse tracking heatmap after averaging across participants

However, mouse tracking has also several drawbacks:

- The first place where the mouse pointer is located is quite important as the observer may look for the pointer. Should it be located outside the image or in the centre of the image? Ideally, the pointer should initially appear randomly in the image to avoid introducing a bias of the initial position of the pointer.
- Mouse tracking only highlights areas that are consciously important for the observer. This is more a theoretical drawback than a practical one as one should try to predict the overtly interesting regions.
- The pointer hides the image region it overlaps, thus the pointer position is never on the important areas but very close to them. This drawback may be partially eliminated by the low-pass filter step performed after the mean of the whole observer set. It is also possible to make a transparent pointer as in [21].

Mouse tracking was neglected with few publications since [20] and somehow considered as a "poor man's eye-tracking". However the rise of learning-based computational models using deep neural networks, which need huge datasets to provide correct results has changed the situation. Mouse tracking can be done online by a virtually unlimited number of participants allowing the generation of big datasets of mouse tracking data. As eye-tracking can only provide datasets with a limited number of stimuli and users per stimulus, even if they are more precise, the development of mouse tracking has certain advantages that complement eye-tracking. Moreover, the combined use of eye and hand tracking can also provide insight into the deployment of attention in natural tasks [22].

2. Direct measures of attention

EEG: Get the electric activity from the brain

The EEG technique (ElectroEncephaloGraphy) uses electrodes placed on the participant's scalp. Those electrodes amplify the electrical potentials originating in the brain. An issue of this technique is that the skull and scalp attenuate those electrical signals.

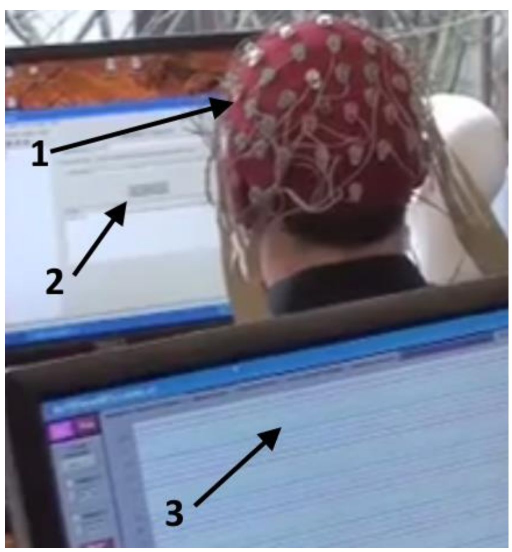

Fig. 10: Example of a research EEG device with a lot of electrodes (1), screen for the participant to visualize stimuli and tasks (2), screen for the operator to visualize the signals (3).

While classical research setups have a high number of electrodes (Figure 10) with manufacturers like [23][24], some low-cost commercial systems like Emotiv [25] are more compact, easier to install and calibrate (Figure 11). While the latter are easier to use, they are obviously less precise.

Fig 11: A low-cost commercial EEG (here the Emotiv EEG system)

EEG studies provided interesting results as the modulation of the gamma band [26] during selective visual attention. Other papers [27] also provide cues about the alpha band modification during attentional shifts.

One very important cue about attention which can be measured using EEG is the P300 event-related potential (ERP).

The work of Näätänen et al. [28] in 1978 on auditory attention provided evidence that the evoked potential has an enhanced negative response when the subject was presented with rare stimuli compared to frequent ones. This negative component is called the mismatch negativity (MMN), and it was observed in several experiments. The MMN occurs 100 to 200 msec after the stimulus, a time that is perfectly in the range of the preattentive attention phase.

Depending on the experiments, different auditory features were isolated: audio frequency [29], audio intensity [30][31][32], spatial origin [33], duration [34] and phonetic changes [35]. All these features were not salient alone, but saliency was induced by the rarity of each one of these features.

The study of the MMN signal for visual attention has been investigated several times in conjunction with audio attention [36][37][38]. But a few experiments were made using only visual stimuli. Crottaz-Herbette in her thesis [39] conducted an experiment in the same conditions as for auditory MMN and she shown a high increase of the negativity of the evoked potential when seeing rare stimuli compared with the evoked potential when seeing frequent stimuli. The visual MMN occurs from 120 to 200 msec seconds after the stimulus. The 200 msec frontier approximately matches the 200 msec needed to initiate a first eye movement, thus to engage the "attentive" serial attentional mechanism. As for the audio MMN detection, no specific task was asked to the subject who only had to hear the stimuli, this MMN component is thus preattentive, unconscious and automatic.   This study and others [40] also suggest the presence of a MMN response for the somatosensory modality (touch, taste, etc…) The MMN seems to be a universal component of the brain response reflecting an unconscious preattentive process. Any unknown stimulus (novel, rare) will be very salient as measured by P300. Rarity or novelty is a major driver of the attentional mechanism for visual, auditory and all the other senses.

Functional imaging: fMRI

MRI stands for Magnetic Resonance Imaging. The main idea behind this kind of imaging system is that human body is mainly made of water which is itself composed of hydrogen atoms that have a single proton. Those protons have a magnetic moment (spin) which is randomly oriented most of the time. The MRI device uses a very high magnetic field (B0) to align the magnetic moment of a small fraction of protons in the patient's body. Radio Frequency (RF) pulses are used to drive the proton spins into a plane orthogonal to B0. As the spins re-orient or "relax" parallel to the orientation of B0, RF emissions are produced. Those emissions are captured and an inverse Fourier transform is used to construct an image where clear gray levels mean that there are more protons, therefore, more water in the body parts (like in fat for example) and a darker gray levels reveal regions with less water (like bones for example).

MRI was initially an anatomical imaging technique, but it was soon discovered that the susceptibility artifact created by iron in the blood could be used to measure blood volume and oxygenation. Since blood volume and oxygenation respond to the metabolic demands of neural tissue, they can be used as a proxy for neuronal activity. In that way, when a region in the brain, for example, is activated, than the blood may have an increased flow. The hemodynamic response has multiple components that bear a complicated relationship to the metabolic and electrical activity of the neural tissue. Nevertheless, fMRI imaging is capable of detecting the areas in the brain which are more or less active and has become a great tool for neuroscientists to visualize which area in the brain responds during an attention-related patient exercise (Figure 12).

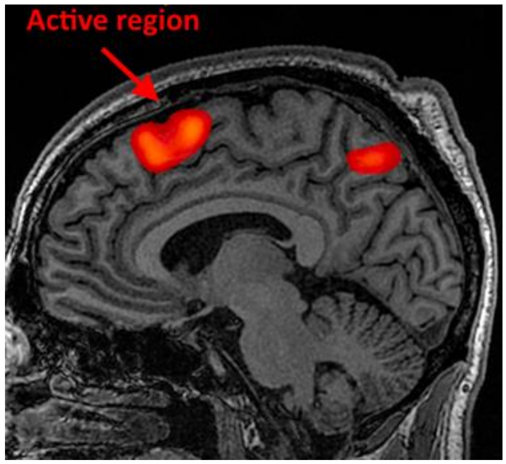

Fig 12: Example of fMRI output: red active regions superimposed on an anatomical MRI sagittal image. Adapted from [44].

Functional imaging: MEG

MEG stands for MagnetoEncephaloGraphy. The idea is simple: while the EEG detects the electrical field which is heavily distorted when traversing the skull and skin, MEG detects the magnetic field induced by this electrical activity. The magnetic field has the advantage of not being influenced by the skin or the skull. While the idea is simple, in practice the magnetic field is very weak which makes it very difficult to measure. This is why the MEG imaging is relatively new: the technological advances that allow MEG be effective are based on SQUID (Superconducting Quantum Interference Devices). The magnetic field of the brain can induce electricity in a superconducting device which can be precisely measured. Modern devices have spatial resolutions of 2 millimetres and temporal resolutions of some milliseconds. Moreover, MEG images can be superimposed on MRI anatomic images which helps to rapidly localise the main active areas. Finally, participants in MEG imaging can have an upright seated position (Figure 13) which is more natural during testing than the horizontal position of fMRI or PET scan.

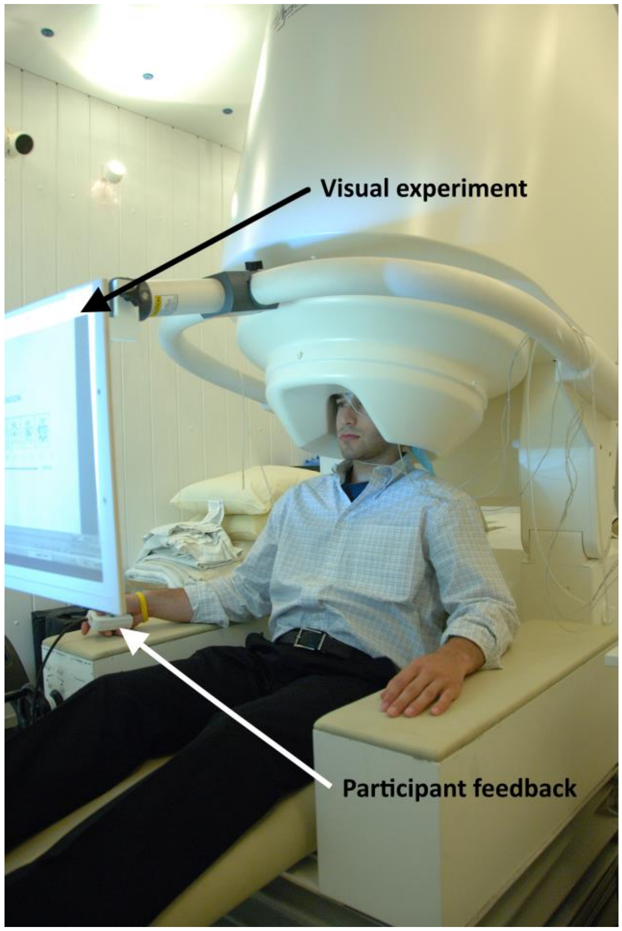

Fig 13: A participant set into the MEG device and a visual experiment. Adapted from [45]

Functional imaging: PET Scan

As for fMRI, PET scanning (Positron Electron Tomography) is also a functional imaging tool and it can thus produce also a higher signal in case of brain activity. The main idea of PET scan is that a mildly radioactive substance which is injected to the patient releases positrons (anti-electrons which are particles of the same properties as en electron but with positive charges). Those positrons will almost instantaneously meet an electron and have a very exo-energetic reaction (called annihilation). This annihilation will transform the whole mass of the two particles into energy and release gamma photons in two opposite directions which will be detected by the scanner sensors. The substance which is injected will go and fixate on the areas of the brain which are the most active, which means that those areas will exhibit a high number of annihilations. As for fMRI, the PET scan let the neuroscientists know which areas of the brain are activated when the patient is performing an attention task. Figure 14 shows an example of the use of PET scan to see the influence of a flickering visual pattern in the brain.

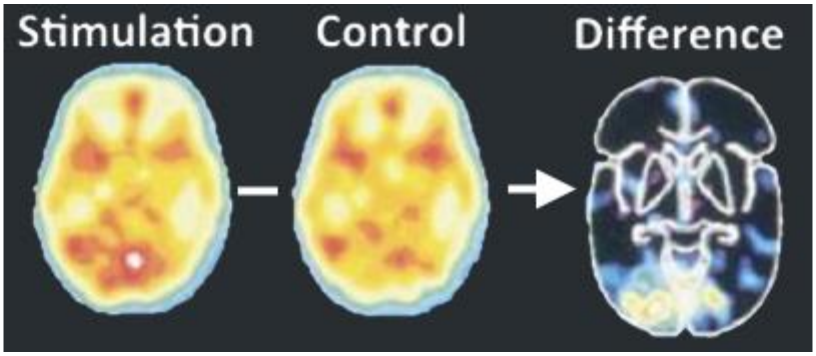

Fig 14: Example of output in case of a repetitive visual pattern (flickering). The difference let us see the areas activated by the stimulus. Adapted from [43].

Complementary techniques to manipulate brain activity: TMS or tDCS

TMS stands for Transcranial Magnetic Stimulation and it uses electromagnetic induction to stimulate a precise region of cortex. A current passing through a coil of wire generates a magnetic field. Rapid variations of this magnetic field induce a transient electric field which in turn influences the membrane potential of nearby neurons.

Beginning with 1980s, TMS has been used first for clinical diagnostic and then in psychiatric therapy. It is now also used in conjunction with other imaging modalities such as fMRI, PET scans and even with EEG devices.

Indeed, imaging techniques allow to find the active areas of the brain for a given task. However, they cannot say which part of those regions and when exactly they are really necessary to solve the task. By interfering with the normal functioning of a brain area, TMS, which has a very good spatio-temporal resolution provides cues about when and where exactly a brain area is making its critical contribution to behaviour.

Figure 15 shows a TMS which influences EEG signals (top-right), fMRI images (bottom-left) and PET scan (bottom-right).

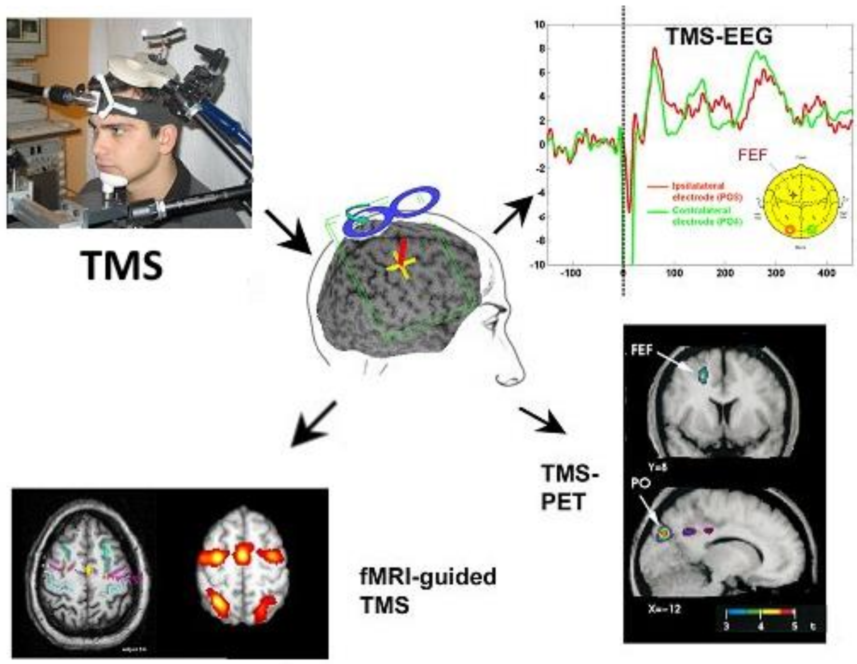

Fig 15: Top-left: a TMS setup; Top-right: EEG modification following a TMS; Bottom-left: fMRI images response after the TMS; Bottom-right: PET scan response after the TMS. Adapted from [46].

Transcranial Direct Current Stimulation (tDCS) is another method which aims in providing neurostimulation. The difference with the TMS is it uses constant current delivered to the brain area of interest via electrodes on the scalp.

Functional imaging and attention

Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have been extensively used to explore the functional neuroanatomy of cognitive functions. MEG imaging becomes to be used in the field as in [41]. In [42] a review of 275 PET and fMRI studies of attention type, perception, visual attention, memory, language, etc. are described. Depending of the setup and task a large variety of brain regions seem to be involved in attention and related functions (language, memory). This findings support again the idea that at the brain level, there are several attentions and their activity is largely distributed across almost all the brain. Attention goes from low-level to high level processing, from reflexes to memory and emotions and across all the human senses.

Summary

- Eye-tracking remains a gold standard mainly in engineering and computer science even if it is used also in psychology.
- Mouse-tracking can be more and more used with the need to build very large stimuli datasets to model attention in computer science.
- In neuroscience, fMRI has the best spatial resolution, EEG/ERP and MEG the best temporal resolution.
- fMRI has become one of the most used methods in neuroscience.
- The use of TMS or tDCS in conjunction with other imaging techniques provides precise cues about when and where exactly a brain area is making its critical contribution to behaviour.

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