What is attention?

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The study of attention: a transversal approach

Human attention is a self-evident mental phenomenon that is active during every single moment of awareness. It was studied first in philosophy, followed by experimental psychology, cognitive psychology, cognitive neuroscience and finally computer science for modeling in humans and machines. These studies emerged sequentially, but add one on top of the others as the layers of an "attention onion" (Figure 1).

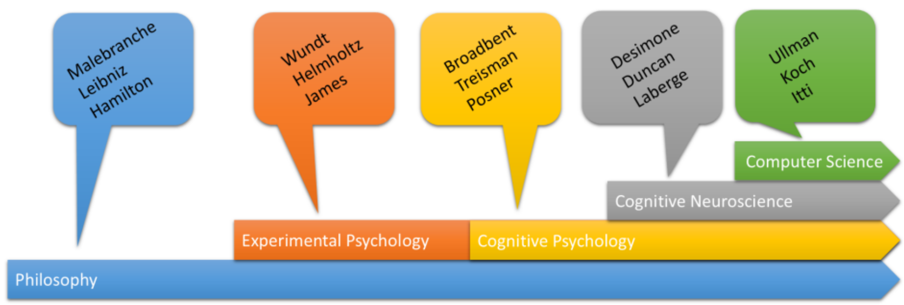

Fig. 1 Attention history and the attention onion: an accumulation of research domains.

Due to the highly diverse applications of attention, a precise and general definition is not easy to find. Moreover, views on attention have evolved over time and research domains. This chapter is structured into two parts. In the first part, we briefly survey the long history of related research from philosophy to cognitive psychology, to which were added cognitive neuroscience and computer science. The second part of the chapter covers different aspects of attention in an attempt to arrive at a working definition.

1. A short history of attention

Attention seems almost absent from any serious writing until the modern age. How did philosophers miss such a key concept from the ancient times to the Enlightenment? Part of the answer is probably that attention is such a self-evident part of life that nobody really noticed it until recently.

Conceptual findings: attention in philosophy

An early and important inquiry into human attention was that of Nicolas Malebranche, a French Oratorian priest who was also a philosopher and follower of Descartes. In his “De la Recherche de la Verité” (Concerning the Search after Truth) published in 1675, Malebranche focused on the role of attention in providing structure in scene understanding and thought organization. He also saw attention as the basis of free will, writing that “the occasional cause of the presence of ideas is attention… and it is easy to recognize, that this is the principle of our freedom” [1]. Thus from the very beginning attention was seen as linked to volition and consciousness.

In the 18th century, G. W. Leibniz introduced the concept of “apperception” which refers to the assimilation of new and past experience into a current view of the world [2]. Leibniz’ intuited an involuntary form of attention (known today as “bottom-up” or “stimulus-driven”), which is **needed for a perceived event to become conscious**. Here attention is viewed as a reflexive and involuntary gate to consciousness.

In the 19th century, Sir W. Hamilton, a Scottish metaphysician, challenged the previous view on attention, which consisted in thinking that humans can only focus on a single stimulus at once. Hamilton noted that when people throw marbles, the placement of about seven of the marbles could be remembered [3]. This finding opened the way to the notion of “**divided attention.**” The limited span of divided attention led about one century later to the famous paper of G.A. Miller, “The Magical Number Seven, Plus or Minus Two” in 1956 [4].

Attention in experimental psychology

After the first philosophical investigations, attention entered a scientific phase when approached by the emergence of experimental psychology in the 19th century. By studying individual differences in the ability of trained astronomers to judge the transit of a celestial body through a telescope, W. Wundt introduced the study of consciousness and attention to the field of psychology [5]. He interpreted this observation error as the time needed to **switch voluntarily one’s attention from one stimulus to another** and initiated a series of studies on the speed of mental processing, made possible by new methods of measuring simple and choice reaction times pioneered by F. Donders [6]. Here attention comes to be related to reflection and not reflex alone.

In the second half of the 19th century, H. Von Helmholtz, in his “Treatise on Physiological Optics” [7] noted that despite the illusion of seeing our entire visual environment at the same spatial resolution, humans need to move their eyes around the whole visual field “because that is the only way we can see as distinctly as possible all the individual parts of the field in turn”. Although his experimental work mainly involved the analysis of the eye movement scanpath (overt attention), he also noted the existence of a covert attention, which is the ability to focus on different parts of a scene without moving the eyes. Von Helmholtz focused on the role of attention as an answer to the question **“Where” the objects of interest are**. Adding to the concepts of reflex attention and divided attention, the notion of parallel versus serial processing was born.

In 1890, W. James published his textbook “The principles of psychology” [8] and remarked again that attention is closely related to consciousness and structure. According to James, attention makes people perceive, conceive, distinguish, remember, and shortens reaction time. He indeed linked attention to the notion of data compression and memory. He also developed a taxonomy of attention that distinguished between “passive” and “voluntary” attention. Contrary to Von Helmholtz, James was more focused on the fact that attention should answer the question of **“What” are the objects of interest**.

Attention in cognitive psychology

Between the very beginning of the 20th century and 1949, the mainstream approach in psychology was behaviorism, which focused almost exclusively on the external causes of behavior. During this period, the study of mind was considered as barely scientific and few important advances were achieved in the field of attention. Despite this “hole” in the study of attention, important work was done on so-called interference effects. One of the most famous examples, the “Stroop Effect,” was reported by J. R. Stroop [9], who showed that reaction times are considerably lengthened when a single stimulus affords two conflicting responses, for example reading a red-printed word such as “GREEN” as opposed to reporting the color of the ink in which the word was printed. Attention was invoked as a means to resolve the response conflict.

After the Second World War, a vastly more technological world emerged. Advances in information theory, statistical decision theory, and, perhaps most importantly, digital computing gave rise to the information age. Human performance in complex environments ranging from battlefields to factory floors became a central concern. The study of attention made a tremendous comeback. To the behaviorist view, which states that the organism’s behavior is controlled by stimulus-response-outcome associations, cognitive psychology showed that behavior can be modulated by attention. The resurgence of attention begun with the work of C. Cherry in 1953 on the “cocktail party” paradigm [10]. This approach models how people select the conversation that they are listening to and ignore the rest. This problem was called “**focused attention”, as opposed to “divided attention”**.

In the late 1950's, D. Broadbent [11] proposed a "bottleneck" model in which he described the selective properties of attention. His idea was that **attention acts like a filter (selector) of relevant information** based on basic features, such as color or orientation for images. If the incoming information matches the filter it can reach awareness (conscious state), otherwise it will be discarded. At that time, the study of attention seemed to become very coherent and was called "early selection". Nevertheless, after this short positive period, most of the findings summarized by Broadbent proved to be conflicting.

The first "attack" came from the alternative model of Deutsch and Deutsch [12] who used some properties of the cocktail-party paradigm to introduce a **"late selection" model**, where attentional selection is basically a matter of memory processing and response-selection. The idea is that all information is acquired, but only that which fits semantic or memory-related objects is selected to reach awareness. This is an opposite view to Broadbent who professed an early selection of the features before they reach any further processing.

New models were introduced like the attenuated filter-model of A. Treisman [13] which is a softer version than Broadbent's bottleneck and which let stimuli with a **response higher than a given threshold through the filter**, thus determining the focus of the selective attention.

Later, in 1980, Treisman and Gelade [14] proposed a new "feature integration" theory, where attention occurs in two distinct steps. First, **a preattentive parallel effortless step** analyzes objects and extracts features from those objects. In a second step, those **features are combined to obtain a hierarchy of focus** attention which pushes information towards awareness.

Despite its importance, the feature integration theory was also highly disputed. Other theories emerged as M. Posner [15] **spotlight supporting a spatial selection** approach or D. Kahneman [16] and his theory of capacity supporting the idea of **mental effort**.

In the late 1980s, a plethora of theories on attention flourished and none of them was capable of accounting for all previous findings. According to H. Pashler [17], after several decades of research in cognitive psychology, more questions were raised than answers given. As a provocative rejoinder to the famous "Everyone knows what attention is" proposed by James a century before, Pashler declared that "No one knows what attention is."

The need for new approaches: after the late 1980s "crisis"

Attention deals with the allocation of cognitive resources to prioritize incoming information in order to bring them to a conscious state, update the scene model and memory and influence behavior. Between consciousness, memory and behavior, attention was revealed to be much more complex than initially expected and some people even questioned whether attention was a single concept or, rather, that there are several different forms of attentions. The number of issues and the complexity of the nature of attention led to an interesting move in splitting attention studies from one single community into two different communities.

The cognitive neuroscience community has the goal of getting further into the theoretical and biological nature of attention using simple stimuli. The arrival of advanced tools such as functional imaging, EEG, MEG, or single-cell recordings in awake, behaving subjects allow them to make huge steps towards relating neural recordings with behavioral correlates of attention.

The segment of the computer science community working in the field of attention has a goal of making the concept work with real data such as images, videos, audio or 3D models. From the late 1990s and the first computational models of visual attention the cognitive neuroscience and computer science approaches have developed in parallel, one trying to get more insight on the biological brain and the other trying to get results which can predict eye movements and other behavior for real-life stimuli and environments. Even if the computational attention community led to some models very different from what is known to happen in the brain, the engineers' creativity is impressive and the results on real-life data begin to be significant and the applications endless.

Attention in cognitive neuroscience

Cognitive neuroscience arrived with a whole set of new tools and methods. If some of them were already used in cognitive psychology (EEG, eye-tracking devices, for example) others are new tools providing new insights on brain behavior:

- Psychophysiological methods: scalp recording of EEG (electroencephalography: measures the large scale electric activity of the neurons) and MEG (magnetoencephalography: measures the magnetic fields produced by electrical currents in the brain) which are complementary in terms of sensitivity on different brain areas of interest.
- Neuroimaging methods: functional MRI and PET scan images which both measure the areas in the brain which have intense activity given a task that the subject executes (visual, audio …). Magnetic resonance spectroscopy can provide information about specific neurotransmitters.
- Electrophysiological methods: single-cell recordings, which measure the electro-physiological responses of a single neuron using a microelectrode system. While this system is much more precise, it is also more invasive.
- Other methods: TMS and TDCS (transcranial magnetic stimulation and transcranial direct current stimulation, which can be used to stimulate a

region of the brain and to measure the activity of specific brain circuits in humans) and multi-electrodes technology which allows the study of the activity of many neurons simultaneously showing how different neuron populations interact and collaborate.

Using those techniques two main families of theories have been constructed.

The first and most well-known model is the biased competition model of Desimone and Duncan on [18]. The central idea is that at any given moment, there is more information in the environment than can be processed. Relevant information always competes with irrelevant information to influence behavior. Attention biases this competition, increasing the influence of behaviorally-relevant information and decreasing the influence of irrelevant information. Desimone explicitly suggest a physiologically plausible neural basis that mediates this competition for the visual system. A receptive field of the neuron is a window to the outside world. The neuron reacts only to stimuli in this window and is insensitive to stimulation in other areas. The authors assume, that the competition between stimuli takes place if more than one stimulus shares the same receptive field. This approach is very interesting as each neuron can be seen as a filter by itself and the neurons receptive field can vary from small and precise (like in the primary visual cortex V1) to large enough to focus on entire objects (like higher visual areas in the temporal and parietal lobes). This basic idea suggests different domains of attention (location-based, feature-based, object-based, attentional bottleneck) in a very natural and elegant way. Moreover, a link is achieved with memory based on the notion of attentional templates in working memory which enhance neuronal responses depending on previous acquired data. This idea is embodied in the selective tuning model of Tsotsos in 1995 [19].

A second family of models was developed by Laberge in late 1990s [20]. It is a structural model based on neuropsychological findings and data from neuroimaging studies. Laberge conjectures that at least three brain regions are concurrently involved in the control of attention: frontal areas, especially the prefrontal cortex; thalamic nuclei, especially the pulvinar and posterior sites, the posterior parietal cortex and the interparietal sulcus. Laberge proposes that these regions are necessary for attention and all these regions presumably give rise to attentional control together. While cognitive neuroscience brought a lot of new methods and information to cognitive psychology, attention is still far from being fully understood and a lot of work is undergoing in the field.

Attention in computer science

While cognitive neuroscience focuses on researching the biological nature of attention, a different angle arose in the 1980s with the improvements in computational power. Building on the Feature Integration Theory of Treisman and Gelade [14] C. Koch and S. Ullman [21] proposed that the different visual features that contribute to attentive selection of a stimulus (color, orientation, movement, etc.) are combined into one single topographic map, called the

”saliency map”. The saliency map integrates the normalized information from the individual feature maps into one global measure. Bottom-up saliency is determined by how different a stimulus is from its surround at several scales. The saliency map provides the probability for each region in the visual field to be attended. This saliency map concept is close to that of the “master map” postulated in the feature integration theory by Treisman and Gelade.

The first computational implementation of Koch and Ullman architecture was achieved by Laurent Itti in his seminal work [22]. This very first computational implementation of an attention system takes as an input any image and outputs a saliency map of this image and also the winner-take-all-based mechanism simulating the eye fixations during scene analysis. From that point, hundreds of models developed first for images, then for videos, and some for audio or even 3D data very recently.

From the initial biologically-inspired models a number of models based on mathematics, statistics or information theory arrived on the “saliency market,” making better and better predictions about human attention. These models are all based on features extracted from the signal (most of the time low-level features but not always), such as luminance, color, orientation, texture, motion, objects relative position or even simply neighborhoods or patches from the signal. Once those features are extracted, all the existing methods are essentially based on the same principle: looking for “contrasted, rare, surprising, novel, worthy-to-learn, less compressible, or information maximizing” areas. All those terms are actually synonyms and they all amount to searching for some unusual features in a given context. This context can be local (typically center-surround spatial or temporal contrasts), global (whole image or very long temporal history), or it can be a model of normality (the image average, the image frequency content). Very recently learning is more and more involved in computing saliency: first it was mainly about adjusting model coefficients given a precise task, now complex classifiers like deep neural networks are beginning to be used to both extract the features from the signal and train the most salient features based on ground truth obtained with eye-tracking or mouse-tracking data.

2. So … what is attention?

The trans-disciplinary nature of attention naturally leads to a lot of different definitions. Attention deals with the allocation of cognitive resources to prioritize incoming information in order to bring them to a conscious state, update a scene model, update memory and influence behavior. But several attention mechanisms were highlighted especially from Cherry’s cocktail party phenomenon. A dichotomy appeared between divided attention and selective attention. From there, clinical observations led to a model of attention divided into five different “kinds” appeared. One can also talk about different kinds of attention that rely on gaze or not, or that use only image features versus memory and emotions… While its purpose seems to be the relation between the outer world and inner consciousness, memory and emotions, the clinical manifestation of attention tends to show that there might be several attentions.

Overt vs. covert: the eye

Overt versus covert attention is a distinction that was noted at the very beginning of psychological studies on attention. Overt attention is manifested by changes in posture that prepare sensory receptors for expected input. Eye movements, head movements, external ear (pinna) movements, changes in pupil size and so forth are all examples of overt attention. Covert attention does not induce eye movements or other postural changes: it is the ability to catch (and thus be able to bring to consciousness) regions of a scene which are not fixated by the eyes. The eye achieves mainly 3 types of movements which are dues to the non-uniform distribution of receptive cells (cones and rods) on the retina. The cones which provide a high resolution and color are mainly concentrated in the middle of the retina in a region called “fovea”. This means that in order to acquire a good spatial resolution of an image the eye must gaze towards this precise area to align it on the fovea. This constraint led to mainly three types of eye movements:

1. Fixations: the gaze stays a minimal time period on approximately the same spatial area. The eye gaze is never still. Even when gazing a specific location, micro-saccades can be detected. The micro-saccades are very small movements of the eye during area fixations.
2. Saccades: the eyes have a ballistic movement between two fixations. They disengage from one fixation and they are very rapidly shifted to the second fixation. Between the two fixations, no visual data is acquired.
3. Smooth pursuit: a smooth pursuit is like fixation on a moving object. The eye will follow a moving object to maintain it in the fovea (central part of the retina). During smooth pursuits, more rapid small corrections can be done to correct position errors.

Modeling overt attention attempts to predict human fixation locations and the the dynamical path of the eye (called the eye “scanpath”).

Serial vs. parallel: the cognitive load

While focused, sustained and selective attention deal with a serial processing of information, alternating and divided attention deal with parallel processing of several tasks. These distinctions show that attention can deal with information both serially and in parallel. While there is a limit to the number of tasks which are processed in parallel during divided attention (around 5 tasks), in the case of pre-attentive processing, massively parallel computation can be done. Some notions such as the “gist” [23] seem to be very fast and able to process the entire visual field to get a first and very rough idea about the context of the environment. The five kinds of attention follow a hierarchy based on the degree of focus, thus the cognitive load which is needed to achieve the attentive task. This approach is sometimes called the clinical model of attention:

1. Focused attention: respond to specific stimuli (focus on a precise task).
2. Sustained attention: maintain a consistent response during longer continuous activity (stay attentive a long period of time and follow the same topic).
3. Selective attention: selectively maintain the cognitive resource on specific stimuli (focus only on a given object while ignoring distractors).
4. Alternating attention: switch between multiple tasks (stop reading to watch something).
5. Divided attention: deal simultaneously with multiple tasks (talking while driving).

Bottom-up vs. top-down: memory and actions

Another fundamental property of attention needs to be taken into account: attention is a mix of two components referred to as bottom-up (or exogenous) and top-down (or endogenous) components. The bottom-up component is reflex-based and is driven by the acquired signal. Attention is attracted by the novelty of some features in a given context (spatial local: a contrasted region, spatial global: a red dot while all the others are blue, temporal: a slow motion while before motion was fast …). Its main purpose is to alert in case of unexpected or rare situations and it is tightly related to survival. This first component of attention is the one which is the best modeled in computer science as the signal features are objective cues which can be easily extracted in a computational way.

The second component of attention (top-down) deals with individual subjective feelings. It is related to memory, emotions and individual goals. This component of attention is less easy to model by computers as it is more subjective and it requires information about internal states, goals, a priori knowledge, or emotions. Top-down attention can be itself divided into two sub-components:

1. Goal/Action-related: Depending on an individual current goal certain features or locations are inhibited and others receive more weight. The same individual with the same prior knowledge responds differently to the same stimuli when the task in hand is different. This component is also called “volitional”.
2. Memory/Emotion-related: This process is related to experience and prior knowledge (and the emotions related to them). In this category one can find the scene context (experience from previously viewed scenes with similar spatial layouts or similar motion behavior) or object recognition (you see your grandmother first in the middle of other unknown people). This component of attention is more “automatic”, it does not need an important cognitive load and it can come along with volitional attention. The other way around, the volitional top-down attention cannot inhibit the memory-related attention

which will still work even if a goal is present or not. More generally, bottom-up attention cannot be inhibited if there is a strong and unusual signal acquired. If someone searches for his keys (volitional top-down), he will not take care about a car passing by. But if he hears a strange sound (bottom-up) and then recognizes a lion (memory-related top-down attention), he will stop searching for the keys and run away. Volitional top-down attention is able to inhibit the other components of attention only if they are not very intense.

Attention vs. attentions: a summary

The study of attention is an accumulation of disciplines ranging from philosophy to computer science and passing by psychology and neuroscience. Those disciplines study sometimes different aspects or views of attention, which leads to a situation where a single and precise definition of attention is simply not feasible.

To sum-up the different approaches attention is about:

- eye/neck mechanics and outside world information acquisition: the attentional "embodiment" leads to parallel and serial attention (overt versus covert attention)
- allocation of cognitive resources to important incoming information: the attentional "filtering" is the first step towards data structuring (degree of focus and clinical model of attention)
- mutual influence on memory and emotions: passing of important information to a conscious state and get feedback from memory and emotions (bottom-up and memory-related top-down attention)
- behavior update: react to novel situations but also manage the goals and actions (bottom-up and volitional top-down attention)

Attention plays a crucial role, partly conscious and partly unconscious, from signal acquisition to action planning going through the main cognitive steps… or maybe there are simply several attentions and not only one. At this point in time, this question still has no final answer.

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