

The future of attention models: information seeking and self-awareness

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This book contributes to the crucial endeavor of understanding and modeling human attention. It gives an overview of physiological and computer science models, an extensive approach to model validation, as well as new trends and applications of attention models. It also paves the way for further investigations. Some directions for future research are discussed in the next section, in relation to the major contributions summarized above. In the second section, a perspective on issues beyond attention, such as higher level processing and consciousness, is provided. We propose that human attention can be viewed as a suite of computational strategies that are essential for autonomous behavior by agents both natural and artificial. The study of attention should go beyond filtering of sensory data to develop an understanding of how relevant and valuable information is actively gathered by agents who possess an integrated awareness of both their internal goals, needs and abilities and external sources of sustenance or danger. This kind of awareness implies an ability to model both the environment and the self that acts within that environment. Understanding the computational mechanisms underlying active, goal-oriented attention may be a first step toward artificial consciousness.

1. Perspectives in attention modeling

1.1 Models

1.1.1 Computing eye scan-paths from saliency maps

Most saliency models take color images as input and produce saliency maps that estimate the probability distribution of the gaze in the image. The static nature of these maps could be an issue for some applications as these models do not predict the temporal sequence of human fixations (also called scan-path). What is the order of fixations? How is the image seen dynamically? Some models like FSM [31], DVA [32] or ESAL [33] propose algorithms to predict the scan-path from a saliency map. However, this question deserves to be investigated more deeply. Indeed, the dynamic nature of attention was less investigated in the saliency models than in the visibility models (see chapter 7).

1.1.2 Modeling visual attention with learning algorithms such as Deep Neural Networks

Recently, with the advent of deep learning in many areas, some general multi-layer deep networks have been proposed to detect human fixations (see chapter 7). Although the neural network methods are very effective, some issues remain to be solved by further research to mix the advantages of those models with more classical hand-crafted ones. First, current deep neural networks remain unclear about the nature of the learned representation and about their results. This is not the case for hand-crafted models which are often clear and interpretable. In neural networks, it is not easy to distinguish learning of bottom-up factors from top-down factors or even viewer biases like the center bias. The second major issue is the dependency of deep neural network on databases. The database containing eye tracking data is small compared to databases in other fields like object recognition, etc. There are solutions like mouse tracking or webcam-based systems to build medium sized databases but to the detriment of precision. Moreover, the database has to be representative of each situation because the neural network will be trained on this database.

1.1.3 Multi-modal modeling of attention

One of the future trends will be to aggregate results from attention algorithms on videos, but also on sound or 3D objects. This integration will drastically augment the already numerous engineering applications of attention modeling. Of course those new models will need new ground-truth and new validation techniques, but this effort is crucial to boost the attention modeling community and to augmented its visibility both in other research communities and in industry.

1.1.4 Curiosity: uncertainty reduction through guided exploration

When humans encounter a novel environment, one of their first priorities is to learn whom, what and where to attend. Random, novelty-driven exploration has to be balanced with hypothesis-driven mechanisms for identifying sources of valuable or meaningful information [37]. This kind of everyday goal-directed information seeking can be called curiosity. Reward circuits in the brain respond not only to the likelihood and amount of reward, but to uncertainty [38]. Quantifying uncertainty is essential for decision-making [39]. Attention can be thought of as a mechanism to seek information that reduces uncertainty through guided exploration. Future studies should focus on the neural and computational mechanisms of attention and decision-making in environments where risk, uncertainty and ambiguity can be controlled. An autonomous agent, such as a robot, should be able to pose questions that are relevant to its current situation and to formulate plans to seek answers to those questions.

1.2 Model validation

1.2.1 Exploring databases with new classes of stimuli

Currently, saliency models for still images are very effective on natural images. However, their performance is frequently disappointing on other kinds of stimuli like websites, paintings, etc. Indeed, for such stimuli, there is a significant decrease in performance. To address this issue, more databases like [34] have to

be collected on diverse sources (websites, advertising, etc.) to understand what attracts attention when observing stimuli different from classical “natural images”.

1.2.2 Large-scale human data during natural explorations of videos

Recently, large scale datasets have become a necessity in several domains of computer vision. In saliency, it is complicated to obtain large scale datasets due to the nature of the ground-truth. Conventional eye tracking studies are time consuming. However, there are alternatives such as mouse tracking [35] or webcam-based eye tracking [36] but they are currently applied only on still image databases.

1.2.3 Metrics for comparing temporal sequences of eye fixations

As is the case for saliency models, standard metrics to compare the output of attention models and human fixations are static. They do not take into account the temporal sequence of human fixations. Although in [37] the authors proposed some dynamic metrics to compare two scan-paths, there are still too few databases and models providing temporal sequences of fixations.

1.2.4 Study of biases inside stimulus categories

As described in [38], there are different classes of stimuli, such as noisy images, indoor pictures, etc. For each type of image, major biases exist either from viewers who are watching static and dynamic scenes or from features of the stimuli. The impact of salient object size in outdoor pictures or different kind of movements in videos are addressed in [39]. These studies show how saliency models manage the size of salient objects or videos from static or moving cameras. They also help to have a better understanding of current model biases and show how to improve them. The recording of new databases with other biases or the addition of new categories inside existing datasets is needed.

1.2.5 Other application-based validation frameworks

A new trend in attention model validation is to have application-based protocols. In chapter 19 for example, a system is established to compare several attention models for a precise application (CBIR), as the rankings might be different between the existing models depending on the application of interest.

1.2.6 Audio-visual validation based on eye tracking data

There is no easy way to validate the use of audio information in saliency models because there is no auditory ground-truth and the dimensions of audio and video information are different. The idea is thus to find a way to build an audio-visual validation protocol. Eye tracking data acquired with visual and audio-visual conditions should be used. All saliency models for videos could be validated by only one condition inside the validation framework. Some audio features could be used to weight the saliency results on videos and better predict where people attend.

1.2.7 Deployment of attention during the performance of natural tasks

Attention is often studied in situations where subjects are given various cues or reinforcement. In other words, the tasks are structured to guide attention to locations, features or objects that have been chosen by the experimenter. This begs the question of how subjects naturally deploy attention when performing everyday tasks such as driving, making a sandwich, or playing sports. Ballard, Hayhoe and colleagues [36] have recently developed an immersive virtual reality system for recording eye, head, and hand movements when human subjects are performing simple tasks. Such systems allow experimental control over external variables like novelty, reward and context while imposing minimal constraints on subject behavior. In the future, such systems can be combined with mobile EEG recording to map the brain activity during natural, goal-directed behavior.

2. Attention beyond information filtering

2.1 Structure, semantics and objects

In chapters 1 and 2, we saw that attention is the gate between the outer world (or subconscious in the case of dreams) and consciousness. Part of the attention process occurs before information reaches awareness; it is pre-attentive or reflex and can use a parallel processing strategy to acquire data. The attentive process is conscious and uses a serial discovery strategy based on selected data from the pre-attentive acquisition. Serial deployment of attention is highly dynamic and depends on a number of factors:

- Bottom-up: related to information maximization of the field of view where features are extracted and processed,
- Top-down: depends on the task on hand or on specific object recognition,
- Previous eye fixation location: the dynamical process of vision provides different bottom-up cues depending on the fixation location.

The eye scan-path can be very different from one person to another depending on the image content, the initial eye fixations and the importance of the task. Attention acts as an information filter and prioritization strategy, transforming a huge amount of unstructured information to a serial discovery of the most interesting areas or objects. This eye scan-path shows that attention not only discovers important areas, but also seeks to find how those areas are related (object-subject relationship). Moreover, attention due to object changes (motion) has a huge impact on the final result and is obtained using a different pathway in the brain than an object-oriented attention. Indeed, visual signals mainly follow two different pathways in the brain, a dorsal and a ventral, one focusing more on object recognition (what?) and the other on space and movement (where?). This distinction between the fundamental question of what (the objects/subjects) and where/how (their interaction) are directly related to the minimal semantics of a sentence composed of a subject/verb/object. In [1], it is hypothesized that

children already base their first thoughts (in a language non-specific way) as a “transfer” (verb) between an “agent” (subject) and a “willing recipient” (object). When children learn a language, they actually try to encode this first conscious representation into a given language, as an expression of their consciousness.

Beyond being a simple information filter, attention gives cues on which areas (subject/object) are interesting in the scene and their changes (verb) leading to the first notion of semantics. It seems that the influence of the attentive system goes a beyond the initial role of selecting the information that gains access to awareness, it also intends to provide it with a structure. Indeed in chapter 15, it is shown how attention can be related to the notions of “proto-objects” or “objectness” which are the first steps towards the notion of object. This represents a milestone in the understanding of our environment.

2.2 Emotions, memory and actions

Attention and memorability are heavily interlinked. While the influence of emotions and memory on attention is obvious and this influence is part of the definition of top-down attention, in the other direction (attending towards emotions and memory) things are less clear. Nevertheless, even if the links are not as obvious as one would think, the first step towards memorizing an object may require attention. In chapter 18, the link between visual attention and image memorability is detailed as an application of attention modeling.

In the brain, a basic structure within the thalamus provides very interesting clues about a possible relationship between attention, memory, and emotions. This is the Papez circuit (Figure1) which was initially seen as a mechanism for emotions [5].

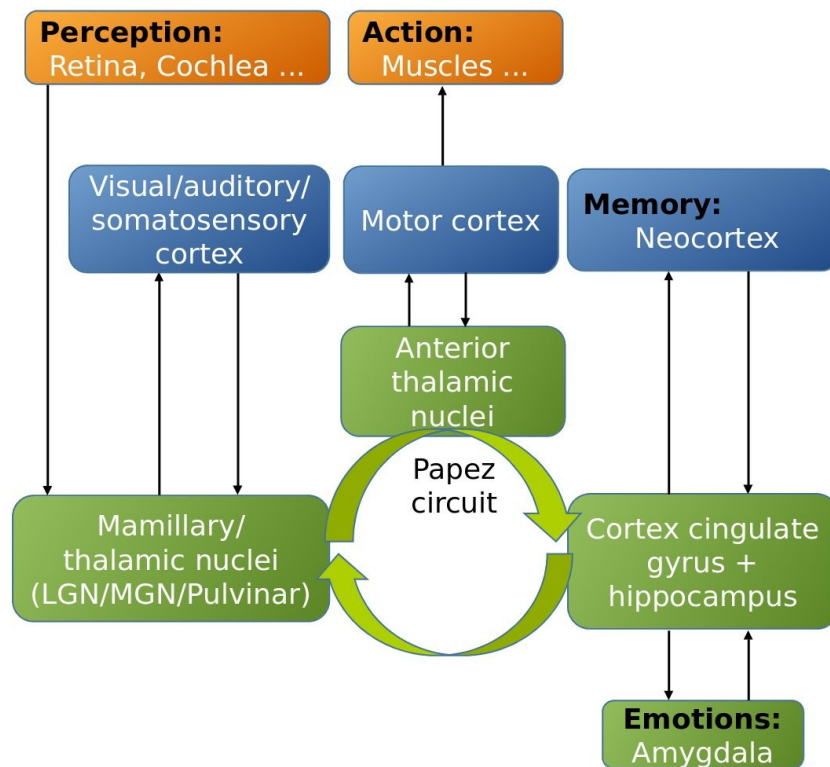


Figure 1: A simplified schematic view of Papez circuit. In green the areas which are directly involved in the circuit. This circuit is linked to both emotions and memorability. Indeed, if impaired, new data will not go into the long term memory, but older recollection are not affected.

The main element of this circuit is the hippocampus which is related to episodic and spatial memory [6].

At the rostral end of the temporal lobe, a collection of nuclei called the amygdala is involved in emotions. The emotions related to the amygdala are mainly negative but positive emotions also evoke a response in this area [7]. The amygdala also responds to high interest or unusual images which attract attention [8].

At the other side of the Papez circuit one can find the mamillary body and the anterior thalamic nuclei. The mamillary body relays the output of the hippocampus and amygdala to the anterior thalamus and has an important role in spatial memory [3]. The anterior thalamic nuclei are linked to action and the motor cortex. Other thalamic nuclei that are important in sensory processing and attention are the lateral geniculate nucleus (relays signals from the retina to visual cortex [4]), the medial geniculate nucleus (auditory perception), and the pulvinar which is directly related to attention by modulating or gating sensory signals in relay nuclei [9].

It is very difficult to isolate locations in the brain which are responsible for complex tasks such as attention (see chapter 4) or memory, but the Papez circuit is of particular interest because in the limbic system, attention, memory, action and emotions have a close anatomical proximity and are all needed in the process of memory formation. Thus, attention is heavily interconnected with

emotions, memory, and action. Indeed the effects of an agent's own body on its environment are highly important in scene understanding, and it also has a crucial impact in the feeling of self-awareness and ownership which are at the basis of consciousness.

2.3 Towards consciousness

In [2] Schmidhuber links the notion of attention to compression progress. It is interesting to note that the concepts of compression and prediction are not only emphasized in [2], but this concept is quite well accepted as a driver of our brain. The idea of matching sensory inputs to stored patterns from memory to predict what will happen in the future is also present in [10] where the interaction of neocortex, hippocampus and thalamus is central to the model. The brain is analyzed as an encoding problem, complete with error-correction codes.

In [2], the incoming data has regularities and irregularities: each time regularities are found, they can be further compressed and simplified. A better explanation of the environment results in its simplification, and thus its compression. A complex concept which is very well compressed will be considered as subjectively beautiful. For example, a beautiful face will be one close to the average face previously learned, as only few bits are necessary to code the deviation of the new face from the previously learned one. Also symmetries are important regularities which can be compressed and which can be seen as subjectively beautiful. The approach of Schmidhuber implies that a subjectively beautiful woman, for example, has a face with perfect symmetries and very close to the average of faces that the observer has seen (related to the observer family and social class). But beautiful does not mean interesting. In [2], the author states that beauty is interesting only during a given time period, as long as it is new. He thus defines the interest or attention as the derivative of the subjective beauty. A beautiful object attracts attention only if the beauty (compression) progresses. For example, a perfect beautiful woman for a subjective observer will attract attention at the beginning, but this attention rapidly fades. If this woman has a small defect, the need for compression of this small defect will provide more interest to this woman than to a perfect one. It is important to differentiate the subjective beauty due to information compression from the beauty coming from external rewards (linked to emotions and memory). In [2] attention is also linked to consciousness as compression induces the use of symbols or codes summarizing regularities with a high occurrence probability in the information. In the same way, a subject which occurs very frequently in a subjective observation of the world is the observer or agent himself, thus it is very efficient for him to find a code for himself, and by doing this, the agent becomes self-aware and conscious.

There are several models of consciousness. In those models, attention plays an important role as in [11] where the colliculus, in addition to its role of fusing attention of several modalities (visual and auditory attention) on a unique topographic map, also generates a simulation of the sensory world that corresponds to primary (sensory) consciousness. The interaction between

perception and action (eye orientation) is a key to the development of consciousness.

In [12] attention is an emerging property due to subsets of neurons which activate at the expense of other groups related to stimuli which will thus remain unattended. When no stimulation is present, groups of neurons related to a past stimulus can activate and synchronize with other related groups of neurons. In that way, the network pays attention to a stimulus which is actually not present but occurred in the past. This way of thinking about a stimulus is viewed in [12] as the emerging of consciousness, which is like “attention to memory”.

In one model of consciousness, attention and consciousness are viewed inseparable: the CODAM model of John Taylor [13]. Taylor developed and refined his model until [14] which is a vibrant and complete legacy of 10 years of research on the notion of consciousness. CODAM stands for “Corollary Discharge of Attention Movement.” The importance of attention is signified by its appearance in the name of the model. This model is based on control theory. Modules representing goals integrate top-down attention with a module for the input signal which focuses on bottom-up attention. Two other key modules are used in CODAM. One is the working memory buffer and the other is the corollary discharge, which is the key of the model. This corollary discharge is a copy of the attention movement control signal and it activates the working memory buffer. The corollary discharge signal is an internal copy of the location-to-be-attended and it can be interpreted as a signal of the ownership of the about-to-be-experienced content as well as a signal of guarantee of the content-to-be-acquired to be the one that the agent choose to acquire. This signal of ownership and self-awareness or correct self-identification is of a crucial importance in the building of the “I” and the consciousness. The CODAM model also helps explain pathologies like schizophrenia where a higher weight to the corollary discharge is enough to amplify the self-awareness so the subject is too involved with his own thoughts and cannot cope with the reality of an external world.

2.4 The rise and fall of consciousness

CODAM is one of the models where attention is tightly related to consciousness. But is this hypothesis necessary? In [15] the author insists on the clear separation of consciousness and attention. Attention may only select among already conscious concepts. Also attention is a process where not all of the attended regions reach the conscious state: looking is not watching and hearing does not mean listening. Attention can be parallel and serial. During parallel strategies, the gist of a scene or other global details can become conscious without the need of being explicitly attended. However, if attention is considered in both covert and overt aspects, it is hard to find examples where attention and consciousness do not match. Even if attention is NOT consciousness, it is safe to argue that the relationship between the two concepts is very tight and that full consciousness requires some form of attentive mechanism.

Given these considerations, measuring the state of attention can be an indirect measure of the state of consciousness. Meditation studies using EEG, PET or

fMRI imaging have found that 1) there might be an increased attentional control in the frontal brain regions [16][17], 2) this occurs at the same time primary visual cortex regions acquiring signals from the outside world decrease [18][19]. The above studies seem to lead towards the possibility that meditation is an augmented consciousness state, but focused on the self and not on the external world.

A strange case was reported in [20] in which a young woman was in a vegetative state following severe brain injuries sustained in a car accident. While no overt sign of awareness could be observed, an fMRI study suggested that she was able to hear, understand speech, and follow doctor instructions. Indeed, when she was asked to think about playing tennis for example, her brain acted in a very similar way as a control patient. This is a case showing that despite no visible awareness sign consciousness can still be at work.

A final question is how attention and consciousness initially develop and later decline throughout the lifespan of an individual. In [21][22] evidence of REM sleep as early as around the 6th months of fetal development suggests that even with rudimentary auditory sensing, spatial coding of sound and processing of structure and meaning are already at work. Following the CODAM theory these early attentional signs suggest that the first sense of ownership begins to be set up before birth. However, the exact mechanisms of attentional development remain unknown.

On the other side of life, during agony, one would expect attention and consciousness to slowly fade until their complete shutdown when vital functions cease. While work relating agony to attention and consciousness is very sparse, some evidence supports the idea that, contrary to the slow fading of consciousness, the approach of death induces massive cerebral activity closer to attentional fireworks than slow shutdown. As [20] shows in the case of a vegetative state, the visible state of a person is not necessarily related to their awareness or its state of consciousness. In [23][24] the authors show that in rare cases, patients can recall auditory details during general anesthesia where attention and consciousness are presumably inhibited or absent.

In [26], the authors performed EEG measurements on rats during waking periods, during anesthesia, and after induced cardiac arrest. While awake, the rats showed a normal EEG. During anesthesia, the activity drastically decreased. But, just after the heart stopped, EEG activity exceeded activity levels found during the conscious waking state (especially in the gamma range, which is related to visual attention [25]). Contrary to expectations, attention-related EEG signals were greater than normal for roughly 30 seconds after the heart stopped beating. In [27], similar results are described, this time demonstrating hyperactivity of the sympathetic system. Sympathetic system arousal generally occurs during stressful situations that require rapid preparation of the body to fight or flee from danger. This hypothesis might explain part of the sudden near-death sympathetic hyperactivity in the brain as a kind of hyperawareness might

improve the odds of survival in cases where the animal is able to escape or recover from a near-death situation.

In humans, about 10% of dying people are conscious during their agony. Within those 10%, it is estimated that 50 to 60% have deathbed visions. A deathbed vision is thus present in most of the deaths where people are conscious, and they consist in visions of dead relatives or friends, religious figures, or a language related to travel [29]. Those deathbed visions are positive visions that comfort the dying and prepare them psychologically for death [30]. The visions are positive, structured and meaningful, in contrast to the case of more chaotic and mostly auditory illusions associated with mental illnesses, dementia, delirium or drugs which are mostly negative and with little meaning [28]. Interestingly the near-death visions in humans could be related to the high arousal in visual attention demonstrated in moribund rats. They are also concomitant with people gazing in fixed regions with few eye movements and dilated pupils, and being reduced social interaction with people nearby. Bottom-up attention seems thus reduced while all the attention focuses on the top-down component which is related to memory and emotions. The state of consciousness of the dying is closer to that experienced during meditation and focus on the self and not on outside. The higher weight of top-down component might explain part of those visions, but it seems difficult to explain them entirely. Another explanation might be a psychological defense against the idea of ceasing to exist and the shut-down of consciousness. But again, this approach probably only partly explain those visions.

These studies show that the shut-down of consciousness is not necessarily slow, but in the very last moments (when physically possible) people experience a very high degree of attention and consciousness before brain death and maybe even after heart stops like in rats. However, due to the lack of scientific experiments and measurements on dying people, it is very difficult to provide an objective view on the topic.

In this book, we focused on attention from the level of single neurons to visual detection, and on through computational modeling of salience and scan paths. Those models are mostly concerned with information filtering, but some applications like image memorability (see chapter 18) go further than simple information filtering. In this last chapter we provided some insights on structure and objects, memorability and the first steps towards consciousness where attention plays a crucial role. We also saw that attention and consciousness are at the very beginning of life (during fetal development) focused inwardly on the self, they then open to others during life, and return again to the self during the natural dying process. How exactly attention begins to work in babies and how it acts in the very final moments of life still remains very speculative and reaches the boundaries of current science.

References

- [1] Goldberg, Adele. *Constructions, A Construction Grammar Approach to Argument Structure.* Chicago University Press, Chicago, Il, 1994.
- [3] Vann, Seralynne D. "Re-evaluating the role of the mammillary bodies in memory." *Neuropsychologia* 48.8 (2010): 2316-2327.
- [2] Schmidhuber, Jürgen. "Driven by compression progress: A simple principle explains essential aspects of subjective beauty, novelty, surprise, interestingness, attention, curiosity, creativity, art, science, music, jokes." *Anticipatory Behavior in Adaptive Learning Systems.* Springer Berlin Heidelberg, 2009. 48-76.
- [4] O'Connor, Daniel H., et al. "Attention modulates responses in the human lateral geniculate nucleus." *Nature neuroscience* 5.11 (2002): 1203-1209.
- [5] Papez, James W. "A proposed mechanism of emotion." *Archives of Neurology & Psychiatry* 38.4 (1937): 725-743.
- [6] Burgess, Neil, Eleanor A. Maguire, and John O'Keefe. "The human hippocampus and spatial and episodic memory." *Neuron* 35.4 (2002): 625-641.
- [7] Garavan, Hugh, et al. "Amygdala response to both positively and negatively valenced stimuli." *Neuroreport* 12.12 (2001): 2779-2783.
- [8] Hamann, Stephan B., et al. "Ecstasy and agony: activation of the human amygdala in positive and negative emotion." *Psychological Science* 13.2 (2002): 135-141.
- [9] Arend, Isabel, et al. ".15-The role of the human pulvinar in visual attention and action: evidence from temporal-order judgment, saccade decision, and antisaccade tasks." *Progress in brain research* 171 (2008): 475-483.
- [10] Hawkins, Jeff, and Sandra Blakeslee. *On intelligence.* Macmillan, 2007.
- [11] Merker, Bjorn. "Consciousness without a cerebral cortex: A challenge for neuroscience and medicine." *Behavioral and Brain Sciences* 30.01 (2007): 63-81.
- [12] Izhikevich, Eugene M. "Polychronization: computation with spikes." *Neural computation* 18.2 (2006): 245-282.
- [13] Taylor, J. G. "Consciousness: theories of." *Handbook of Brain Theory and Neural Computation* (ed. MA Arbib). Cambridge, MA: MIT (2002).
- [14] Taylor, John G. *Solving the Mind-Body Problem by the CODAM Neural Model of Consciousness?.* Springer, 2013.
- [15] Lamme, Victor AF. "Why visual attention and awareness are different." *Trends in cognitive sciences* 7.1 (2003): 12-18.

- [16] Shear, Jonathan, and Ron Jevning. "Pure consciousness: Scientific exploration of meditation techniques." *Journal of Consciousness Studies* 6.2-3 (1999): 189-210.
- [17] Jevning, R., R. K. Wallace, and M. Beidebach. "The physiology of meditation: a review. A wakeful hypometabolic integrated response." *Neuroscience & Biobehavioral Reviews* 16.3 (1992): 415-424.
- [18] Herzog, Hans, et al. "Changed pattern of regional glucose metabolism during yoga meditative relaxation." *Neuropsychobiology* 23.4 (1990): 182-187.
- [19] Baerentsen, Klaus B., et al. "Onset of meditation explored with fMRI." *Neuroimage* 13.6 (2001): 297.
- [20] Owen, Adrian M., et al. "Detecting awareness in the vegetative state." *Science* 313.5792 (2006): 1402-1402.
- [21] Mirmiran, Majid. "The function of fetal/neonatal rapid eye movement sleep." *Behavioural brain research* 69.1 (1995): 13-22.
- [22] Hopson, Janet L. "Fetal psychology." *Psychology Today* 31.5 (1998): 44.
- [23] Osterman, Janet E., et al. "Awareness under anesthesia and the development of posttraumatic stress disorder☆." *General hospital psychiatry* 23.4 (2001): 198-204.
- [24] Sebel, Peter S., et al. "The incidence of awareness during anesthesia: a multicenter United States study." *Anesthesia & Analgesia* 99.3 (2004): 833-839.
- [25] Müller, Matthias M., Thomas Gruber, and Andreas Keil. "Modulation of induced gamma band activity in the human EEG by attention and visual information processing." *International Journal of Psychophysiology* 38.3 (2000): 283-299.
- [26] Borjigin, Jimo, et al. "Surge of neurophysiological coherence and connectivity in the dying brain." *Proceedings of the National Academy of Sciences* 110.35 (2013): 14432-14437.
- [27] Fujiwara, Atsushi, and Hitoshi Kobata. "Paroxysmal sympathetic hyperactivity after near-hanging." *The American journal of emergency medicine* 33.5 (2015): 735-e1
- [28] Janzen, MEd Catherine. "Deathbed Phenomena: Real or Imagined?." (2011).
- [29] Mazzarino-Willett, April. "Deathbed phenomena: its role in peaceful death and terminal restlessness." *American Journal of Hospice and Palliative Medicine* (2009).
- [30] Brayne, Sue, Hilary Lovelace, and Peter Fenwick. "End-of-life experiences and the dying process in a Gloucestershire nursing home as reported by nurses and care assistants." *American Journal of Hospice and Palliative Medicine* 25.3 (2008): 195-206.

- [31] L. Itti, C. Koch, and E. Niebur, "A model of saliency-based visual attention for rapid scene analysis", *IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI)*, vol. 20, no. 11, pp. 1254–1259, 1998.
- [32] X. Hou and L. Zhang, "Dynamic visual attention: searching for coding length increments." in *Proceedings of Neural Information Processing Systems (NIPS)*, vol. 5, 2008, p. 7.
- [33] T. Avraham and M. Lindenbaum, "Esaliency (extended saliency): Meaningful attention using stochastic image modeling", *IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI)*, vol. 32, no. 4, pp. 693–708, 2010.
- [34] L. Yujian and L. Bo, "A normalized levenshtein distance metric", *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, vol. 29, no. 6, pp. 1091–1095, 2007.
- [35] A. Borji and L. Itti, "Cat2000: A large scale fixation dataset for boosting saliency research", *arXiv preprint arXiv:1505.03581*, 2015.
- [36] M. Jiang, S. Huang, J. Duan, and Q. Zhao, "Salicon: Saliency in context", in *Conference on Computer Vision and Pattern Recognition (CVPR)*, 2015, pp. 1072–1080.
- [37] O. Le Meur and T. Baccino, "Methods for comparing scanpaths and saliency maps: strengths and weaknesses", *Behavior research methods*, vol. 45, no. 1, pp. 251–266, 2013.
- [38] C. Shen and Q. Zhao, "Webpage saliency", in *The European Conference on Computer Vision (ECCV)*. Springer, 2014, pp. 33–46.
- [39] P. Xu, K. A. Ehinger, Y. Zhang, A. Finkelstein, S. R. Kulkarni, and J. Xiao, "Turkergaze: Crowdsourcing saliency with webcam based eye tracking", *arXiv preprint arXiv:1504.06755*, 2015.
- [36] Hayhoe M, Ballard D., "Modeling task control of eye movements." *Curr Biol*. 2014 Jul 7;24(13):R622-8. doi: 10.1016/j.cub.2014.05.020. Review.
- [37] Gottlieb J, Oudeyer PY, Lopes M, Baranes A., "Information-seeking, curiosity, and attention: computational and neural mechanisms" in *Trends Cogn Sci*. 2013 Nov;17(11):585-93. doi: 10.1016/j.tics.2013.09.001. Epub 2013 Oct 12.
- [38] Schultz W, Preuschoff K, Camerer C, Hsu M, Fiorillo CD, Tobler PN, Bossaerts P., "Explicit neural signals reflecting reward uncertainty", in *Philos Trans R Soc Lond B Biol Sci*. 2008 Dec 12;363(1511):3801-11. doi: 10.1098/rstb.2008.0152.
- [39] Grinband J, Hirsch J, Ferrera VP., "A neural representation of categorization uncertainty in the human brain", in *Neuron*. 2006 Mar 2;49(5):757-63.