Information Theory and the Distinction between Attention and Awareness

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Contents

I. Introduction

Experiments are able to distinguish between attention and awareness in human subjects. The distinction between attention and awareness is often made by showing that people can attend to a visual stimulus without being aware of it [1]. Some forms of attention without awareness are hard-wired: for example, observers are unable to gain awareness of which eye it is that sees a given input. [2] Other forms of attention without awareness depend on the situation. A very well known example of inattentional blindness occurs when viewers who are asked to watch a video of people playing basketball fail to notice a gorilla passing among the players [3]. I found that research papers rarely state the precise definitions being used for attention and awareness, and consequently do not fully characterise the difference between the two (e.g. [1] [4] [2]). It is also not clear whether there exist only these two distinct variables, or whether attention and awareness exist on a continuous scale.

I suggest that the definitions of attention and awareness are best approached via information theory, and that we should use attention to refer to a divisible capacity and awareness to an indivisible one. In particular, I review information bottlenecks of both attention and awareness. I attempt to harmonise existing definitions, which can help establish a framework for future discoveries, as well as provide a clarification of existing results. Regarding awareness, I suggest that researchers explicitely state either their definition of awareness, or the proxy they are using for awareness (e.g. verbal report).

There are several potential benefits to clarifying our definitions. One benefit is to facilitate communication between researchers. Another benefit is to improve the modeling procedure e.g. for studies of multitasking ability.

II. Definitions of attention, awareness, sensation, and saliency

Some definitions currently in use

Attention is most easily studied and defined in vision, where an eye movement (saccade) towards an item is indicative of attention. The significance of awareness and attention can be described in terms of selectivity [5] : we neither attend to nor are aware of everything we lay our eyes on [6]. “Attention is a selection process where some inputs are processed faster, better or deeper than others” [5].The experimental basis for a selective process is the phenomena of change blindness and inattentional blindness, where a subject is incapable of reporting (e.g. verbally or by pressing a button) a change in the visual field or an unexpected stimulus.

In Section 5.1.1.1 of her recent textbook [7], Zhaoping defines attention as a resource which is applied to or spent on the selected input, enabling this input to be recognized or decoded, and as an act of selection. She notes that both top-down (voluntary) and bottom-up selection are commonly referred to as attending. The saliency of a visual location, the main concern of the

textbook, is defined as the degree to which the location attracts selection by bottom-up mechanisms. Information decoding can refer to information processing both by attention and awareness: object recognition requires perceptual information decoding, whereas grasping a tool or walking up a staircase may only require attentional information decoding (section 6 in [7]).

Vision involves at least two processes, looking and seeing [7]. These correspond to attention and awareness. Although we may have the impression that we are first aware of something, and then look at it, in reality one looks in order to see, i.e. attention precedes awareness. In addition, looking (attention) is dissociable from seeing (awareness), as made clear by the example of brain lesion patients who can correctly manipulate objects in spite of not being able to recognise them [8].

Attention can be defined as information processing that occurs after a preliminary preattentive stage of processing. In vision, information processing takes place at the retina, well before signals are relayed via the optic nerve to the lateral geniculate nucleus (LGN), and further on to V1. This is sometimes referred to as preattentive selection [9]. Preattentive processing is defined as without top-down attentional guidance, i.e. by bottom-up attractions only (see [7] page 196). The role of preattentive processing is generally thought to be to keep as much information as possible in as concise a form as possible. This is referred to as the efficient coding hypothesis [10].

Attention which manifests as exploratory behaviour, as with a cat turning to a bird it has just spotted, is referred to as orienting, or as an orienting response [11]. Orienting can also be defined more generally as any overt form of selection, such as shifting gaze (section 5.1.1 of [7]).

One definition of visual attention is as a “convolution of sensori-motor processing with memory” [12]. In other words, memory, rather than saliency, is the arbiter in allocating further computational resources to sensory information. Again, attention is defined as a resource: “Attention is a selection process where some inputs are processed faster, better or deeper than others, so that they have a better chance of producing or influencing a behavioral response or of being memorized” [12]. This again describes attention as a computational resource, and as a selection process whereby some information is kept and some information is discarded. Facilitation and inhibition of signals is also cited [4] as a role of attention. This highlights the action of amplification, familiar as gain control in electronic signal processing.

Just as Zhaoping defines saliency as a bottom-up phenomenon, so Dehaene [13] distinguishes between top-down attention and bottom-up stimulus strength. He distinguishes between unattended and attended subliminal stimuli, as well as between subliminal and preconscious stimuli (Figure 1). He uses the word conscious for awareness. A preconscious stimuli is defined as one which, if attended, would immediately enter consciousness, as opposed to becoming a mere attended subliminal stimuli. A subliminal stimulus is one that is below the threshold of consciousness.

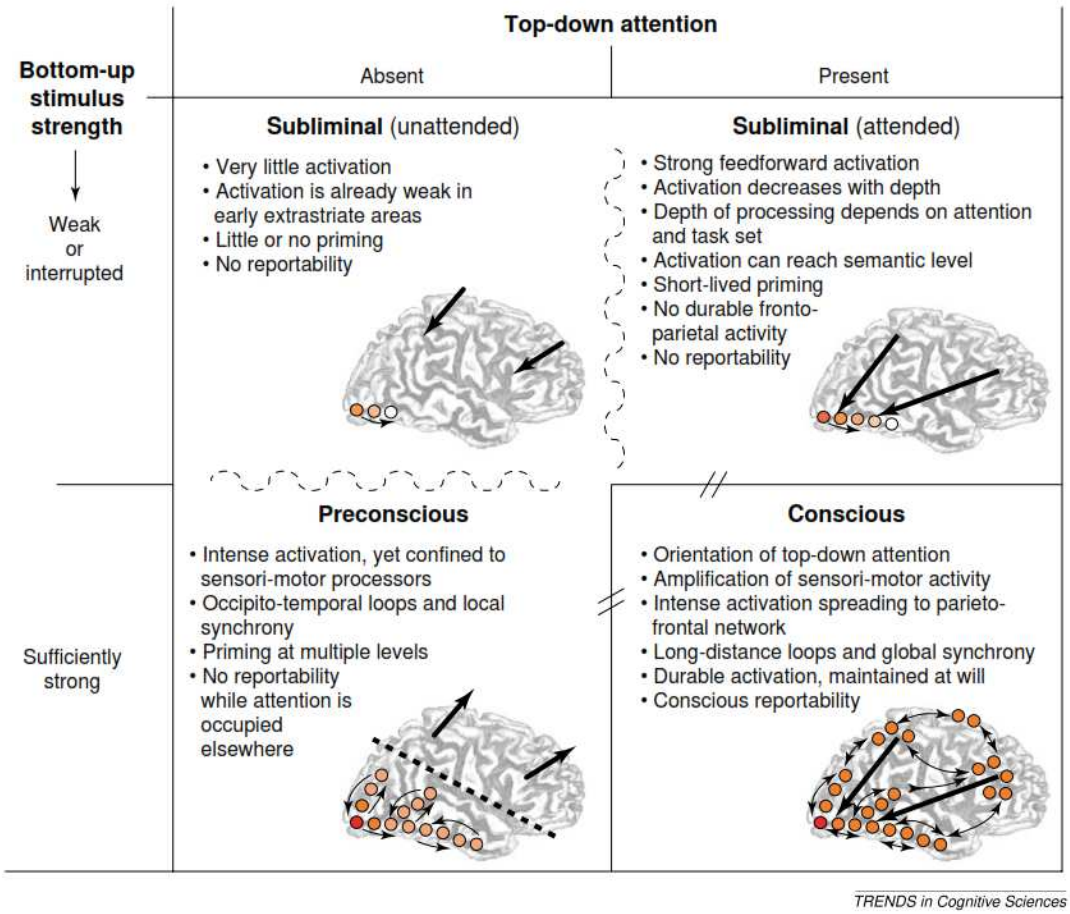

Figure 1. **Dehaene's classification of subliminal, preconscious, and conscious**. From [13].

Dehaene goes into the distinction between attention and awareness: "considerable evidence indicates that without attention, conscious perception cannot occur. In the inattentional blindness paradigm, even a 700-ms stimulus presented in the fovea, when unattended, might fail to be seen", and that "both bottom-up stimulus strength and top-down attentional amplification (whether triggered voluntarily or by automatic attraction) are jointly needed for conscious perception, but they might not always be sufficient for a stimulus to cross the threshold for conscious perception" [13].

Occasionally the words preattentive selection and attention are used instead of attention and awareness, respectively [9].

The only definition I have been able to find of awareness in an experimental setting is the capacity to verbally report, or "access to conscious report" [13]. The adjective associated with awareness is "perceptual", and perception is taken to be a synonym of awareness (see [7] page 209). It is an attractive definition in providing a clear-cut observable: either the subject can or cannot say that they experienced a given stimulus. Yet we have the experience of awareness without access to words, as when rendered speechless by a beautiful sunset. Such experiences make clear that verbal report is not actually a definition of awareness – it is a proxy for awareness. While this

distinction may seem trivial, I believe it is important in maintaining a clear conceptual framework for future research.

Overview of different definitions of attention and awareness			
Early XXth Century	Orienting response	Attention	
Zhaoping & Dayan	Preattentive	Attention	
Zhaoping (later papers)	Saliency	Top-down attention	Awareness
Dehaene	Subliminal		Conscious

Proposed definitions for sensation, attention, and awareness

The definitions I propose are as follows.

Sensation is defined as information from the senses. Photons reaching the retina and absorbed by rod or cone receptors are an example of sensation. So is the information sent by a hair on your arm to its nerve endings in response to a breeze.

Attention is defined as the selection of some of sensation for further processing. Attentional information is defined as the information selected by attention. As such, attentional information is a subset of sensation. In this broad definition of attention, it does not make sense to speak of an indivisible capacity for attending. Just as saliency information in V1 may direct visual attention, so saliencies in other sensory modalities incur choices in what to attend. Even within a given sensory modality there are a myriad of computational choices being made as to how to compress, transmit, and discard information. Each choice is a form of attention, and any loss of incoming information in the nervous system implies attention to what is kept.

Using this definition, it does not make sense to speak of pre-attentive selection. Computations which would have been called pre-attentive selection are subsumed in the definition of attention. If attention and awareness are defined as distinct, and if there is some such thing as pre-attentive selection, it may not be obvious to specify where the boundary is between attention and pre-attentive selection. For this reason the latter term is not used.

I will not explicitly propose a definition of awareness. Since I describe attention as a divisible resource, and since it is common to experience an invariant quality to the sense of self, I propose that awareness is an indivisible quantity. This however does not constitute a full characterisation.

The preceding remark that verbal report is a proxy for awareness rather awareness itself is a useful distinction for further research. Namely, it suggests that there may be other proxies for awareness that do not involve the capacity for verbally reporting the presence of a stimulus. For example, the subjective perception of time may be a proxy for awareness. It might be meaningful to say that awareness increases the more time seems to dilate, and that awareness decreases the more time seems to contract. It is conceivable that there would be some signature of awareness in EEG / MEG readings, which do not require any active reporting by the subject. While such examples may or may not be correct, they may encourage the reader to search for better proxies of awareness.

III. Attentional information is kept or discarded according to saliency

Using saliency to understand attention

Saliency is defined as the extent to which an item stands out relative to its neighbours, e.g. via contrast ; a horizontal bar among vertical bars is said to be salient. An item that is salient is said to be a singleton. The V1 saliency hypothesis states that V1 creates a bottom-up map of visual space by representing the saliency of a location by the highest firing rates of the V1 neurons whose receptive fields cover the location. The most salient location in a scene is the receptive field location of the most active V1 cell [7].

Saliency has the advantage of describing in a computational framework the means by which attention operates. This makes saliency is a theoretically important quantity. Visual saliency is proposed [7] to correspond to neuron firing rates in V1, and while it may not be technically feasible for an experimentalist to measure the firing rates of every neuron in V1, it is at least conceivable. Saliency allows us to understand the implementation of attention. For example, the superior colliculus manifests attention in the direction of gaze, possibly by first reading saliency information computed in V1 [14]. While most studies have been carried out on early visual processing, it is an exciting prospect to establish models of saliency maps for other sensory modalities, and to discover how they may differ or resemble each other in their implementation of attention.

A non-trivial non-attentional selection process is given by eye of origin information [2]. An ocular singleton is an item such as a horizontal bar, which is presented to only one eye, against a background of non-salient items such as vertical bars, which are presented to the other eye. Subjects are unable to report verbally on the existence of an ocular singleton, as eye of origin information does not reach awareness. However, the ocular singleton does capture attention, as shown by decreased search times and eye movement tracking. The primary visual cortex (V1) is the primary domain for neurons which are tuned to eye of origin, suggesting that V1 plays a role in attention, but not awareness. This is an experimental foundation for the idea that V1 creates a saliency map [7].

Statements made about visual attention should be valid for other sensoy modalities. Just as V1 may create an attentional saliency map for vision [7], so early auditory processing may form an auditory saliency map [15]. Saliency can be both bottom-up and top-down: the former takes place in early processing, V1 in the case of vision, whereas the latter involves later processing areas, as for example when a subject is consciously searching for an item in the visual field.

Quantifying information bottlenecks : attentional bottleneck, perceptual bottleneck

The rate at which information can enter the human visual system is estimated at between 10^7 bits [16] and 10^9 bits per second [17]. 10^7 bits per second is the speed of an ADSL/Ethernet Internet connection. The optic nerve transmission capacity is estimated at 10^7 bits per second

[14]. Visual perception speed is estimated at between 30 to 50 bits per second [18], an estimate arrived at via tests of character recognition and object recognition. In other words, awareness has a data rate whose order of magnitude is of about 100 bits per second. From its entry to the visual system until awareness, the data rate is reduced by over 99%. This data rate reduction is cited [7] [9] as constituting an attentional bottleneck, however it would be more precise to speak of this data rate reduction as a perceptual bottleneck, since it concerns awareness rather than attention. Awareness thus has a much narrower bandwidth than attention.

Insofar as retinal compression of data involves some information loss (Figure 2), the selection of what information to keep and what information to discard is defined here as attention. Efficient coding is a trivial form of attention, in that it is conceivable that the same general form of compression with minimal data loss is applied to all incoming sensation, regardless of type or context. Removing redundant representations of information [14] is not classically defined as attention, which is usually considered as involving a more dramatic choice of what information to keep and what to discard. All that matters for the definition given here of attention is that some of the incoming sensory data is lost, i.e. a choice is made on what to keep. Despite the existence of separate terms attention and preattentive, exogenous selection processes which characterise attention can be operative at the preattentive stage [7]. For example, retinal neurons might possibly signal context independent saliency such as at a bright image spot [14]. If saliency is defined as the property of potentially attracting attention, this suggests using terminology whereby attention is active already at the retina, and dropping the term “preattentive”.

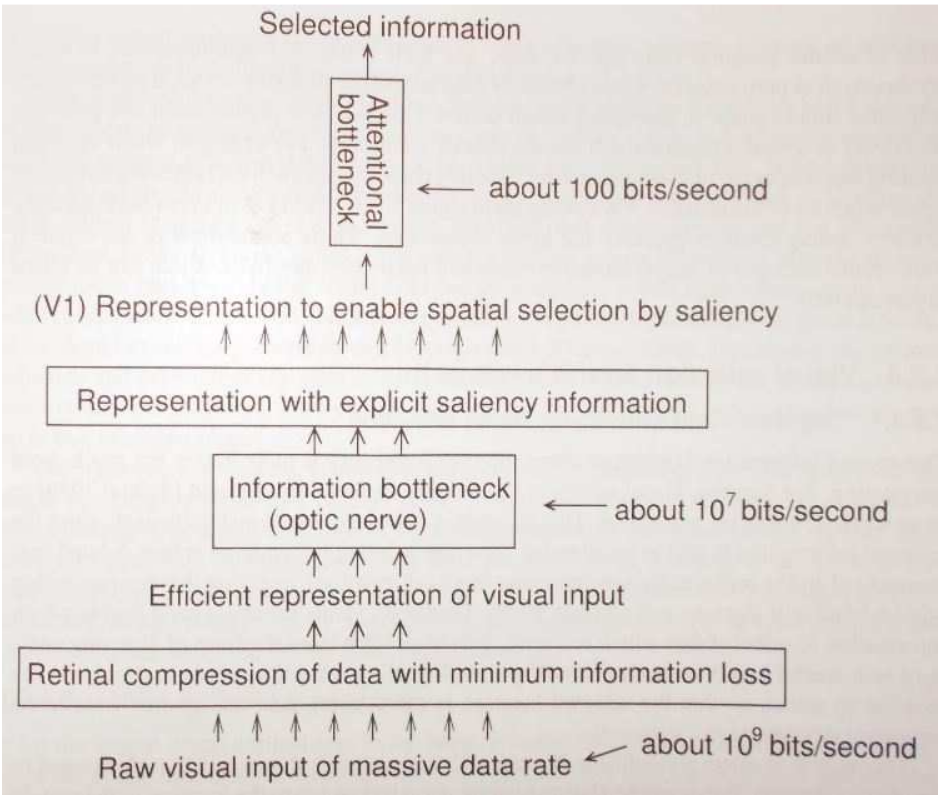

Figure 2. **Reductions in data rate from the eyes to awareness.** From [7]

To quantify in bits the information capacity of attention would be difficult for the entire organism, and would be more relevant when specified for a given modality, say, vision or audition. Even for, say, vision, it may only be relevant to quantify attentional capacity for early visual processing, since later stages of processing most likely share computational resources with other sensory modalities. Based on the axiom of indivisibility of awareness, the perceptual bottleneck is unique. However, it can make sense to speak of several attentional bottlenecks, e.g. an attentional bottleneck for the early processing of each of the senses.

There must be an attentional bottleneck for the information exiting V1, and this bottleneck must be somewhere between 10^7 and 100 bits per second, however it is unclear to me how one might specify the order of magnitude of this bottleneck, given the presence of feedback loops between different brain areas.

Sensory system	No. of sensors	No. of afferents	Total channel capacity (bits/s)	CNS	Psychophysical channel capacity (bits/s)
Eyes	$2 \cdot 10^8$	$2 \cdot 10^6$	10^7	Processing in Central Nervous System	40
Ears	$3 \cdot 10^4$	$2 \cdot 10^4$	10^5		30
Skin	10^7	10^6	10^6		5
Taste	$3 \cdot 10^7$	10^3	10^3		1 (?)
Smell	$7 \cdot 10^7$	10^5	10^5		1 (?)

Figure 3. **Bandwidth of the five senses.** From [19]

The rough estimates given in the above figure suggest that vision has the highest bandwidth in terms of total channel capacity. Vision also seems to be the highest bit rate contributor of sensory information to awareness, which aligns with the feeling people have of the eyes being very expressive. The source states that awareness can only be directed to one sense organ at a time, making 40 bits per second the maximum rate for perception. The source only cites “personal experience” for this statement, and it is not clear to me if the statement is true or if the question is meaningful, since the information pathways of different senses may merge as in auditory-visual synesthesia [20] [21]. In any case, even assuming simultaneous awareness of all senses, the perceptual bottleneck remains at an order of magnitude of 100 bits per second.

IV. Results on the difficulty of multitasking concern awareness not attention

Inability to multitask

Despite the experience people may have of being able to focus on several tasks at once, this usually involves switching focus between tasks very quickly. The tasks are done sequentially, despite the experience of accomplishing them in parallel. True multitasking is notoriously difficult. Drivers may be only be half as good at remembering the objects their eyes fall on while talking on a cell phone than when off the phone, even for highly relevant items such as a child standing on a sidewalk [4].

One neuroscientist is quoted [4] as saying "You're not paying attention to one or two things simultaneously, but switching between them very rapidly." The article authors refer to their work as demonstrating “inattentional blindness”. Applying the preceding definition of attention to these phrases leads to an inconsistency. As defined here, people are constantly paying attention to a myriad of objects simultaneously. Even as a choice is being made as to where to focus your eyes, choices are being made as to how to position your body (sensori-motor attention), and on whether to shift awareness to a passing sound (auditory attention). Insofar as attention and awareness are defined as distinct I do not believe that it is possible to define them in an intuitive way that would be consistent with the referenced article.

Investigating both awareness and attention in multitasking

In such multitasking studies, it seems that attention and awareness are not distinguished, and that the only quantity defined is attention, whcih subsumes the characteristics of both. In the context of multitasking studies, this seems limiting in that both attention and awareness clearly play a role in multitasking. Dancing to music requires both auditory attention and sensori-motor attention, while awareness may instead be entirely focused through the eyes on one’s dance partner. Both have a limited and potentially quantifiable bandwidth. Distinguishing between attention and awareness provides a framework for studying how attention can be multitasked even as awareness cannot be multitasked.

Awareness is postulated to be indivisible, but it is possible that what may be disorders of awareness such as schizophrenia may lead to awareness becoming fragmented. It would be interesting to see if the exceptional “supertaskers” identified [4] as having true multitasking ability are more likely than average to be schizophrenic, or to have some other disorder of attention or awareness.

V. Characterising mental disorders as affecting attention or awareness

Some mental disorders can be be described as deficits of attention or awareness, schizophrenia [22] for example. Schizophrenia has been described as excessive awareness, namely awareness of information processing that should remain inaccessible to awareness [23]. Attention-deficit hyperactivity disorder (ADHD) involves impairing levels of inattention [24], whereas autism spectrum disorder involves difficulty in disengaging attention [25]. Inattentional blindness tests can be used to compare different disorders. For example, schizophrenics are more likely to exhibit inattentional blindness than controls [26]. While tests of attention have been carried out for various disorders, attention is not defined and it is sometimes unclear if the intention is to test awareness or attention.

Time perception studies [27] may also be relevant, and disordered time perception may be a signature of disorders of awareness or attention. Some results tentatively suggest that ADHD subjects have normal time estimations when controlling for IQ [28]. In contrast, disordered time perception has been reported in schizophrenia [29] [30]. The categories of temporal perception are not entirely clear [27], due to the multidimensional nature of time perception [31]. It is also possible that disorders of attention or awareness are correlated with given mental disorders without providing the optimal characterisation of these disorders. The use of such characterisations in the diagnosis and treatment of patients is one way to validate definitions of attention and awareness.

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