Understanding awareness

It's about *time*

by Dr. Hinze Hogendoorn

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His research interests lie in the temporal aspects of perception, particularly vision. How does the brain generate a coherent stream of visual awareness, when different visual features are processed separately in different places in the brain and at different times? And how does it generate the illusion that we live in the present, whereas the neural processes underlying visual perception necessarily take time – thereby incurring delays that are long enough that we should notice them? These are some of the questions that his research seeks to address. This extract relates to the theme "limits" in that it explores the limits of time as perceived by the mind.

As human beings, we are observers: able to become consciously aware of objects and events in the external world. Conscious awareness is perhaps one of our most fundamental capacities: a defining experience, generated by the brain on the basis of sensory information from numerous dedicated brain systems. Understanding awareness has long been an important goal of numerous theoretical and empirical disciplines, including philosophy, psychology, neuroscience, physiology, pharmacology, and even theology (and many others). Many great thinkers as far back as Zarathustra (~1000 BC) have concerned themselves with the question of how the material substance of the body leads to the apparently ephemeral world of thought, mind, and consciousness. Roughly three thousand years later, we have learned a great deal about the relationship between body and mind, and the neural systems and functions that underlie mental processes. Nonetheless, we are a long way from actually understanding how the brain realizes conscious awareness.

Perhaps guided by the observation that many bodily functions are carried out by dedicated, specialized organs, the question of *where* conscious awareness is realized in the human brain has seen extensive interest. Neuropsychological patients, psychophysical and behavioral experiments and modern neuroimaging approaches have characterized the functions and properties of dozens of specialized brain regions. We have identified brain regions involved in sensory processing and integration, memory formation, storage and retrieval, action preparation and execution, and numerous other cognitive functions. Although many disciplines can point out brain areas crucial to becoming aware of particular sensations and experiences within specific domains, the importance of these areas in other modalities is not always evident, and a specialized, localized neural correlate of general awareness has remained elusive. Rather than being localized to a specific brain region, awareness therefore seems to be distributed over numerous cortical (and possibly subcortical) areas. Accordingly, the overarching question of where awareness is realized in the brain might be an ill-posed question.

A dedicated brain region that can be studied from different angles to address interdisciplinary empirical questions is

therefore conspicuously absent. Conversely, there is one factor that plays a role in the study of awareness in any discipline, an all-encompassing aspect that is only occasionally considered: time. Time seems a simple, intuitive notion: a single dimension on which the world smoothly evolves, from future to present to past. Time passes irrespective of what does or does not take place in the meantime; it seems in many ways nearly epiphenomenal. And yet, temporal relationships define the most fundamental properties of the world. For example, causes must precede effects: an event cannot be caused by another event that occurs later. All *changes* in the states of physical objects, as well as internal mental processes, are defined with respect to time. And finally: all processes take time.

We generally take this in stride, without realizing that it has direct and striking implications for our experience of awareness. Mental processes, including the neural processing of perceptual information, take time. When you open your eyes and see the world, by the time you are aware of that visual information, the world has evolved: what you *perceive as present*, has already happened and as such is the past. Despite these delays, we experience that we are aware of, and able to act in, 'the present'. In generating awareness, the brain therefore takes into consideration the time lost during processing. This is anything but a trivial task. It does so with great efficiency, allowing us to interact accurately even with very fast moving objects. In professional baseball or tennis, for example, a ball might move as much as 5 meters or more in the time it takes the brain to process visual information pertaining to its position. Furthermore, different sensory information is processed in different parts of the brain and with different neural latencies. Even within a single modality, such as vision, different features, such as color and motion, are processed at different rates and in different places (e.g., Zeki, 2005). Sensory information pertaining to a single given moment therefore becomes scattered over different brain areas, with different fragments of information becoming 'available' to awareness over a range of times. Nonetheless, we experience a single, smoothly evolving, coherent stream of awareness, indicating that the brain is able to bind (multi-)sensory information across these variable delays into awareness of a single instant. But how does the brain piece together the stream of consciousness from information that is distributed over both time and space?

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Because *becoming aware* is a process which itself takes time, studying the time-course of perceptual processes together with the perception of time itself gives unique insight into the neural mechanisms underlying the *realization* of conscious awareness in the brain. In my research, I approach awareness from a temporal angle, in order to gain insight into the generation of awareness in the human brain. I study the role of time within visual perception specifically, but also investigate other perceptual and cognitive functions involved in the generation of awareness, including attention, causality, and the perception of time itself.

The time-course of perceptual processing

We become aware of only a fraction of the sensory information that enters the nervous system. We quickly habituate to the feeling of the clothes we wear or to the sound of a nearby air-conditioner. We can sit in a restaurant within earshot of multiple conversations and never notice what is said around us. Even the majority of visual information striking the retina never reaches awareness. Substantial evidence implicates *attention* as the cognitive process involved in selecting which information reaches awareness, and which is lost by the wayside (e.g. Treisman & Gelade, 1980). This notion is supported not only by fundamental experimental psychology, but also by the study of neuropsychological patients with hemispatial neglect (who are unaware of half of their world, often across multiple sen-

sory modalities), and the obvious need from an information processing point of view for some kind of filter to curtail the sheer volume of afferent sensory information entering the nervous system.

However, neural processes take time. For any neural processing pipeline, as information flows through the pipeline, it is translated into consecutively more sophisticated, more symbolic representations. In the case of visual perception for example, at any given instant the visual information available at high levels of representation is both older and more abstract than the information available simultaneously in more primitive visual areas.

It is an open question at which of these levels of representation the selection takes place that determines which sensory input reaches awareness and which does not. In the case of attention restricting visual information, for example, attention might select visual information at a very early stage of processing, such that it samples relatively recent visual information, which then requires substantial post-selection processing before it reaches awareness. On the other hand, attention might select information at a more developed level of representation, which is older but requires less processing before being "ready" for awareness.

The key to establishing the level at which selection processes operate is to compare the temporal properties of the *contents* of the percept with the temporal properties of the *processing* of the percept. In one of my experiments, I used electroencephalography (EEG) to show that in the case of visual perception, attention operates on relatively primitive representations (Hogendoorn et al., 2011). We show that neural selection processes take place around 200 ms after the appearance of a stimulus, whereas observers report a percept that is only around 120 ms later than veridical. The representation that attention operates on when selection takes place is therefore on the order of 80 ms old. This finding suggests that attentional selection takes place in relatively early visual areas (Di Russo et al., 2002).

A second point of note is that sensory information continually changes its form as it flows through the processing pathway. This makes the time-course of sensory processing especially informative about the component processes that are involved. In another experiment, we used magneto-encephalography (MEG) to track the representation of a visual feature through the processing pathway (Carlson et al., 2011). We used a multivariate pattern classification approach more traditionally used in functional magnetic resonance imaging (fMRI) to study how the representation of spatial position evolves over the time-course of visual processing. We show that although the spatial position of the stimulus could be decoded from the pattern of brain activity for the entire duration of the stimulus, this decoding performance did not generalize over time-points. In other words, although the spatial position of the stimulus was represented at each moment in time, the *way* in which it was represented was continuously changing. The representation of the spatial position of a visual stimulus therefore evolves extremely rapidly after the initial appearance of that stimulus. Nevertheless, we show that at each stage of processing, the representation of space is structured in a similar way.

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The representation of time

When studying time in perception, it is important to note a subtle but critical distinction: the perception of time is fundamentally distinct from the timing of perception. The former is an ephemeral, subjective experience generated by the brain. It is the aspect of conscious awareness pertaining to the impression of time passing. The latter concerns the objective passage of time involved in the realization of this (or any other) perceptual experience. The two concern fundamentally different timelines. Asking when an event is *perceived to happen* concerns the perception of the occurrence of the event on an internal, subjective timeline: time in the mind. Conversely, asking when an event is *perceived* concerns the occurrence of the perceptual event on an objective timeline: time in the brain.

The fact that we experience the passage of time, that we can perceive the order of events, and that we can bind the multisensory features belonging to a single event into one perceptual representation all indicate that the brain somehow represents time. However, exactly *how* has been a matter of considerable philosophical and empirical debate (Dennett & Kinsbourne, 1992; Eagleman & Holcombe, 2002). What exactly is the nature of the "present", when in fact our awareness of any given instant is the product of sensory information accumulated over a considerable span of time? Given that we are aware of information that in fact pertains to the past, where is the boundary between perceptual awareness and memory? And critically, what is the relationship between when an event is perceived, and when that event is perceived to happen?

This question has seen interest from a range of disciplines, including physiology (Zeki, 2005), philosophy (e.g., Dennett & Kinsbourne, 1992), computational neuroscience (e.g., Buonomano & Merzenich, 1995), and experimental psychology (e.g., Nishida & Johnston, 2002). Broadly speaking, there are two possible ways that the brain might encode time. The most intuitive way for the brain to encode when an event happened is simply by noting when the perceptual processing of that event occurs: using time to code time. This is clearly an effective strategy for longer time-scales, where the brain's own processing delays are negligible. However, we are able to judge temporal intervals substantially smaller than the latency differences introduced by perceptual processes. The question then arises: how?

An alternative option is that the brain represents time explicitly. In this way, the time associated with a particular perceptual feature is encoded separately, in the same way that a letter is stamped with a postmark denoting when it was sent. Irrespective of any delay that might arise in transit, the receiver can deduce on the basis of the postmark when that letter was sent. If perceptual information were similarly accompanied by symbolic representations of where on the timeline that information belongs, this would make the coherence of perceptual awareness a great deal less dependent on the speed of perceptual processes.

At least in the domain of visual perception, it seems like the brain does in fact represent time symbolically. For instance, systematic adaptation to high-frequency flicker, which has previously been shown to distort conscious time perception (Johnston et al., 2006), can cause time-shifts in perception without accompanying time-shifts in processing (Hogendoorn et al., 2010). As a result, two simultaneously presented, synchronously running clocks nonetheless appear offset. This dissociation between the timeline of perceptual processing on the one hand and the internal timeline of conscious awareness on the other therefore demonstrates that the brain maintains a symbolic representation of time that is distinct from the latency of perceptual processing.

This finding provides a solution for the computational problem that arises from the brain's asynchronous processing architecture. Even though sensory features are distributed over a multitude of brain areas, and processed with different latencies, because each feature is tagged with a time-stamp, these features can be actively brought together in order to construct a coherent timeline of conscious awareness. This interpretation also provides an explanation for a number of illusions that appear to violate causality. For example, when a stationary object is flashed in different places in quick succession, it appears to move. This phenomenon is known as apparent motion and is the reason that successive still frames in a video generate the impression of motion. Importantly, the perceived position of an object in apparent motion at a given moment in time depends on where that object will be *in the future* (Hogendoorn et al., 2008). At first glance, this seems to violate causality (how could your percept *now* depend on the future?). However, it does not if one considers that the position of an object at a given time might well be computed a considerable time after the fact, and simply retroactively slotted into the perceptual timeline at the appropriate point. Awareness is therefore not simply the passive endpoint of perceptual processes. Instead, adaptive mechanisms dynamically realign incoming streams of information in order to bring them into register, actively constructing a single, coherent stream of consciousness.

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Implications

The importance of time in the study of awareness is underscored by the observation that certain psychological disorders are associated with impaired time-perception. Schizophrenia patients, for example, perform poorly at time-perception tasks. Hallucinations are a hallmark symptom of this disorder. Given that the internal timeline of awareness seems to be actively constructed, the time-perception deficit associated with this disorder might be closely linked to the hallucinations these patients experience. If a self-generated thought or mental image cannot be linked *in time* to its formation, or recall from memory, then it might well be externally attributed, causing the patient to hear voices, for example.

Although somewhat speculative, this interpretation highlights the broad range of implications that a temporal approach to the study of awareness entails. It provides insight into philosophical questions about the nature of time and the specious present. It suggests an answer to computational problems that arise from the brain's asynchronous processing architecture. It defines the functional role of awareness in terms of an active set of processes, has consequences for models of perception and attention, and might well broaden our understanding of the underlying mechanisms that are disturbed in psychological disorders.

Finally, time provides a way for different disciplines interested in awareness to talk about the same thing. Awareness is by its very nature a topic that is difficult to fully grasp using just a single approach. However, because *time* is an ever-present factor transcending the boundaries of empirical discipline, I believe it has a singular potential for integrating scientific findings from a range of approaches. In my research, I try to find ways in which a temporal perspective can break open the deadlock, bring together methods and perspectives from a range of disciplines, and provide insight into the way conscious awareness is realized in the brain. And it is my conviction that ultimately, understanding awareness will follow inevitably from liberal and creative use of one critical question: "when?".

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