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Opinion

Perceptual awareness negativity: a physiological correlate of sensory consciousness

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Much research on the neural correlates of consciousness (NCC) has focused on two evoked potentials, the P3b and the visual or auditory awareness negativity (VAN, AAN). Surveying a broad range of recent experimental evidence, we find that repeated failures to observe the P3b during conscious perception eliminate it as a putative NCC. Neither the VAN nor the AAN have been dissociated from consciousness; furthermore, a similar neural signal correlates with tactile consciousness. These awareness negativities can be maximal contralateral to the evoking stimulus, are likely generated in underlying sensory cortices, and point to the existence of a generalized perceptual awareness negativity (PAN) reflecting the onset of sensory consciousness.

Highlights

Two prominent neural signals have been proposed as neural correlates of consciousness: an early, modality-specific electroencephalography (EEG) negativity, termed the visual or auditory awareness negativity, and a late, modality-independent positivity known as the P3b.

A critical review of recent research on visual, auditory, and tactile consciousness reveals that over 12 diverse studies found the P3b to be absent despite consciously perceiving stimuli, ruling out the P3b as a true neural correlate of consciousness (NCC).

No convincing evidence for a dissociation between the visual and auditory awareness negativities and consciousness has been reported thus far; furthermore, there is evidence for a similar 'somatosensory awareness negativity'.

The data from these three modalities are consistent with a generalized 'perceptual awareness negativity' arising 120–200 ms after stimulus onset that correlates with perceptual consciousness and originates from the appropriate underlying sensory cortices.

Isolating the neural correlates of consciousness

For more than half a century, psychologists have taken advantage of the fine temporal resolution of electroencephalography (EEG) and magnetoencephalography (MEG) to track the progression of physiological brain activity related to sensory processing [1,2]. Conscious experience fluctuates on a moment-to-moment basis, and the capacity of EEG and MEG to monitor neural responses to a stimulus at the millisecond time scale makes them ideal for investigating the NCC, that is, the minimal neuronal mechanisms jointly sufficient for any one specific conscious experience [3–5].

As the extant literature on EEG and MEG markers of conscious perception is vast, we here only review recent developments and refer the interested reader to the comprehensive discussions in [6–9]. The present review considers several evoked potentials linked to consciously seeing, hearing, or feeling stimuli and considers the extent to which these various potentials reflect a true NCC. We conclude that the existing data are consistent with a generalized and lateralized perceptual awareness negativity (PAN) that arises 120–200 ms following stimulus onset and is likely generated within the underlying sensory cortices.

EEG and MEG correlates of consciousness

A diverse set of neural signals accompanies conscious perception of a stimulus. However, much of this neural activity does not reflect phenomenal consciousness *per se* but rather one or more preceding or subsequent processes, such as expectation, attention, memory, judgements, and decision-making [10–12]. Therefore, once a neural signal has been identified as a potential correlate of consciousness, focused research should try to dissociate consciousness and the proposed NCC in two distinct ways: (i) can the candidate NCC be clearly observed when subjects did not consciously perceive the stimulus? And (ii) can a subject consciously perceive a stimulus even when the candidate NCC is absent?

The logic behind this method is straightforward. Since a genuine NCC must be present when a stimulus is consciously experienced and absent when the same stimulus is not consciously experienced, a few high-quality experiments demonstrating that a given neural signal is present while

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consciousness is absent, or vice versa, can definitively rule out the possibility that the neural signal in question is an NCC, even if dozens of studies have reported a correlative relationship between consciousness and that same neural signal.

Dissociations between consciousness and candidate NCC

Research on NCC commonly takes one of two broad approaches, targeting either neuronal mechanisms that determine the content of a specific phenomenal experience (e.g., seeing a face), known as the content-specific NCC, or the neural substrates that support the ability to have conscious experiences at all regardless of the specific content, known as the full NCC [5]. The former typically involves recording neural activity in conscious subjects while presenting stimuli that are sometimes consciously perceived and sometimes not perceived. This can be achieved via the use of threshold detection tasks, masking techniques, attentional blink, bistable perception, change blindness, and so on.

The full NCC are isolated by comparing waking, sleeping, and anesthetized states in healthy volunteers [5,13] or by observing patients with various disorders of consciousness, such as coma, unresponsive wakefulness syndrome (also known as persistent vegetative state), and minimally conscious states [14–17].

Among the neural signals that have been investigated using these approaches are the mismatch negativity (MMN) [18,19], the semantic N400 [20,21], the face-specific N170 [22–24], the N2 posterior-contralateral (N2pc) [25,26], the modality-independent P3b [27,28], and a modality-specific negativity known as the VAN or AAN [29–33]. The first four have been repeatedly observed to be present in the absence of seeing or hearing the evoking stimulus and, thus, cannot be an NCC (Box 1), but a persistent debate surrounds the P3b and the awareness negativities.

The P3b

The P300, a positive-going event-related potential (ERP) wave with a latency of approximately 250–600 ms is composed of at least two distinct subcomponents, an earlier fronto-central P3a and a later parietally maximal P3b [34–36] (Figure 1). The P3a occurs in states of unconsciousness and reflects automatic, stimulus-driven attentional processes, such as when an unexpected stimulus captures one's attention involuntarily [15,34]. By contrast, the P3b remains the subject of much debate regarding its functional significance [37]. Most often elicited in experimental settings during tasks that involve discriminating infrequent or 'oddball' targets, the P3b has been hypothesized to reflect storage of content in working memory, stimulus-response transformations, context updating, stimulus categorization, and, the subject of this review, conscious perception [2,27,28,38]. Note that in such oddball paradigms, the P3b is observed only in response to the consciously detected deviant stimulus and not to the standard stimuli (which are presumably also consciously detected), contrary to what would be expected from an NCC, which should be evoked by all consciously detected stimuli regardless of their probability.

Even so, based on the multiplicity of studies that have observed a P3b only under conscious conditions (e.g., [27,33,39–47]), the P3b is widely considered to be the most reliable and promising NCC [8,28,48], although its relationship to consciousness has been discussed with more nuance in recent years, even by the most prominent proponents of this view [49]. In particular, the P3b is proposed to index a nonlinear amplification or 'ignition' of cortical activity throughout a distributed 'global neuronal workspace' involving fronto-parietal areas [8,28,41]. An opposing view holds that the P3b is, instead, reflective of postperceptual processing and not consciousness *per se* [9]. Here, we concentrate on assessing the robustness of the available empirical evidence for a

Box 1. Neural signals dissociated from consciousness

Mismatch negativity (MMN): a negative-going waveform (roughly 100–300 ms after stimulus) observed in response to the presentation of a deviant stimulus within an otherwise predictable pattern of stimuli [18,19].

Dissociations from consciousness: the MMN is reliably observed across all stages of sleep [113], in patients with unresponsive wakefulness syndrome (also known as persistent vegetative state [14,55,114–118]), and in patients in a postanoxic coma [119]. Additionally, it fails to distinguish between minimally conscious patients and patients with unresponsive wakefulness syndrome [53–55]. The visual MMN can be evoked in conscious participants by stimuli that are not consciously perceived [67]. Isolating the MMN from the auditory N1 remains a topic of debate [120].

N400: a negative deflection around 400 ms following stimulus onset characterized by increased amplitude in response to semantically unexpected stimuli [20,21,121,122].

Dissociations from consciousness: patients with unresponsive wakefulness syndrome display differential N400 responses to semantically incongruent auditory stimuli [21,123], and the N400 can be elicited in healthy individuals by the presentation of semantically incongruent words rendered invisible using different masking techniques as well as during the attentional blink [20,121,124–126].

N170: a negative waveform elicited by visual face stimuli with a peak latency of 170 ms [22–24].

Dissociations from consciousness: the N170 can be observed even when face stimuli are fully suppressed from consciousness using continuous flash suppression [127,128] or the attentional blink [129] and in rare cases of selective metamorphopsia [72].

N2pc: a negativity in the 200–300-ms time range reflecting the allocation of spatial attention, measured at posterior locations contralateral to the attended stimulus [25,26,130].

Dissociations from consciousness: the N2pc can be elicited by target stimuli that are suppressed from consciousness [25,131–133], although its magnitude is often greater when the evoking stimulus is consciously perceived [26,130,134].

dissociation between the P3b and consciousness, setting aside for now any potential links to theoretical models.

There is variability in the terminology referring to the P3b, which can include ‘P3’ or ‘P300’ [2]; in addition, some have adopted the term ‘late positivity’ (LP) to refer specifically to the difference in

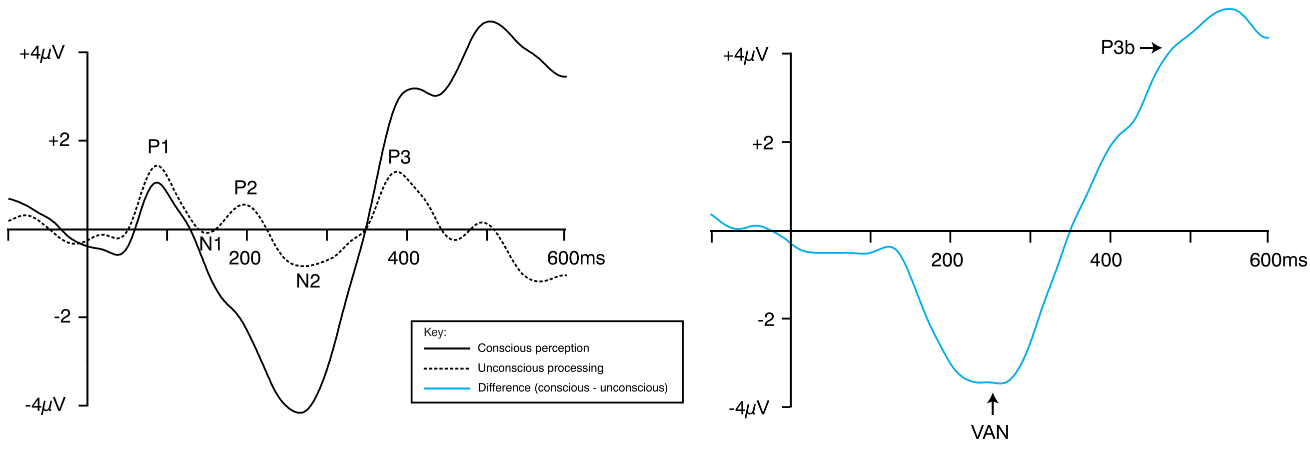

Figure 1. Two electrophysiological candidate correlates of visual consciousness. Left, time course of neural signals recorded from electrodes at occipital–parietal scalp locations (here, PO8), time-locked to the onset of a visual stimulus that was or was not consciously perceived. Right, difference signal obtained by subtracting the unconscious from the conscious condition. This reveals both a visual awareness negativity (VAN) as well as a P3b. These grand-averaged data (*N* = 16) are replotted from [64], with the unbroken black trace depicting a condition in which a face stimulus was consciously seen and task relevant and the broken black trace depicting a condition in which the same face stimulus was unconsciously processed due to inattentional blindness.

P3b amplitude between conscious and unconscious conditions [9]. Accordingly, papers that use the terms 'LP' or 'P3/P300' in their reporting are considered here if the relevant signal has the characteristics of the P3b.

Stimuli from multiple sensory modalities can elicit a P3b, and studies in patients with disorders of consciousness using auditory stimuli have reported a correlative relationship between the P3b and consciousness [50,51]. However, while P3b activity reliably differentiates healthy control participants from patients with disorders of consciousness, it often fails to distinguish between patients who are conscious but impaired, patients who are minimally conscious, and patients with unresponsive wakefulness syndrome [52,53]. In fact, the P3b may not be elicited at all in many minimally conscious and conscious patients with disorders of consciousness, even under conditions that elicit a robust P3b in controls [53,54]. Ignoring the lack of a P3b response in such patients risks overlooking the critical difference between conscious and unconscious patients.

Caution must be taken when considering studies of patients with disorders of consciousness, especially since there is greater variability in the latency and topography of the P3b in these patients above and beyond the substantial variability already observed in healthy controls [55,56]. However, the P3b tends to be robust to the statistical effects of such variability, remaining significant despite wide variations in amplitude and latency [56]. This makes the notable failure to elicit a P3b in 10 of 11 minimally conscious patients in one study even more striking [54] as well as the lack of a significant P3b across 68 recordings from minimally conscious patients and 24 recordings from conscious-but-impaired patients reported by another, which did, by contrast, find a highly significant P3b in their control group of 14 healthy volunteers [53]. These studies cast significant doubt on the hypothesis that the P3b is an NCC.

A growing number of studies with neurotypical participants describe dissociations between stimulus consciousness and the P3b. The P3b tracks stimulus visibility before the formation of expectations about the stimuli, but ceases to distinguish between seen and unseen stimuli once expectations have been formed [57]. Furthermore, the P3b correlates with perceptual consciousness during tasks that engage higher-level cognitive processes (e.g., evaluating the magnitude of masked digits), but not during lower-level tasks (e.g., discriminating the color of masked digits) [58]. Similarly, stimulus identification, but not detection, correlates with the P3b [59,60].

Studies manipulating the task relevance of stimuli have helped distinguish the genuine NCC from postperceptual processes [10]. Using either traditional masking or inattentional blindness to manipulate stimulus visibility while separately controlling task requirements, numerous studies over the past decade found that the P3b is only present when stimuli are task relevant [61–67]. Recent work in the auditory and somatosensory domains has produced the same results regarding the P3b; only when stimuli are task relevant do they evoke a P3b, and only then does the P3b correlate with conscious perception [68–70]. One experiment used an inattentional deafness paradigm that paralleled the inattentional blindness paradigms used by preceding studies [61–67], and their results were consistent across visual and auditory modalities; regardless of participants' stimulus awareness or lack thereof, the P3b only reflected consciousness when the stimulus was task relevant [68].

Another study compared neural activity during a standard tactile detection task and a tactile–visual matching task, the latter intended to dissociate stimulus detection *per se* from the task requirements, while keeping stimulus characteristics the same [69]. Only when stimulus detection was the primary task did the P3b correlate with consciousness; in the matching task, when both the presence and the absence of the stimulus were equally task relevant and equally meaningful, the P3b no longer had any correlation with conscious perception.

This evidence indicates that the P3b is reflective of postperceptual and task-related processes, not conscious perception, and neatly explains the finding mentioned earlier that the P3b is only elicited by deviant stimuli in oddball paradigms; once a pattern has been established, the deviant stimulus is the target relevant to the task, while the standard stimuli are effectively task-irrelevant distractors.

Note that the type of dissociation between the P3b and consciousness is distinct from that of the four neural signals discussed in Box 1; while the MMN, N400, N170, and N2pc can be present in the absence of consciousness, the P3b can be absent despite the presence of consciousness (i.e., the reverse dissociation). A few case studies [71,72] and experiments with neurotypical participants [73,74] have offered some preliminary indications that the P3b may be evoked in the absence of consciousness, but there remains considerable debate regarding the validity and replicability of such studies (e.g., [48]). Thus, it may be possible that the P3b is a sufficient but not a minimally sufficient, that is, a necessary, marker of stimulus consciousness.

The diverse research discussed here, using a multitude of distinct methods, consistently reports a clear absence of a P3b despite the subject consciously perceiving the stimulus; these repeated demonstrations of a dissociation make it clear that the P3b cannot be an NCC.

VAN and AAN

Negative-going EEG and MEG signals in the 100–300-ms time range have been repeatedly observed to correlate with consciousness in the visual and, more recently, auditory modalities while being resistant to the effects of task requirements or response conditions [29–33,56,75–79]. Referred to as the VAN and AAN (most likely closely related to the N1 and to the awareness-related negativity (ARN) in audition [30,75,76]), these signals are isolated by calculating the negative amplitude difference in neural signals between consciously perceived and non-perceived stimuli during the 100–300-ms time range (Figure 1) [9,80]. The VAN is maximal over posterior regions [32], while the AAN is maximal at more anterior scalp sites [33]. While the magnitude of the VAN is largest over regions contralateral to the inducing stimulus, this is less pronounced for the AAN [32,75,81–83], compatible with the idea that these potentials reflect activity in early and/or mid-level, topographically organized visual and auditory cortical regions.

Like the P3b, the VAN and AAN have been linked to theoretical frameworks for consciousness and are often cited as support for models that emphasize the importance of early recurrent processing to consciousness [5,9,83,84]. Again, however, our purpose here is to assess the promise of these neural signals as potential NCC rather than to attempt to link them to larger theories.

The VAN has been studied much more extensively than the AAN, and most evidence has firmly supported the hypothesis that the VAN is an NCC (e.g., [27,29,56,62,77–79,81,85–89]).

Six studies, though, failed to observe a VAN under conditions where it should be expected. Upon review, however, these experiments suffer from a few critical problems, the most common being a failure to account for the spatial lateralization of VAN topography. Five of the six studies used target stimuli that were lateralized to one hemifield, but the authors failed to consider the lateralization of the VAN during data analysis by combining signals from both hemispheres [40,43,90–92]. Subsequent studies closely following the procedures of two of these studies

[43,90] while controlling for lateralization in their analyses did observe a VAN [32,81]. Thus, we discount these putative failures to confirm a VAN.

The multiplicity of electrophysiological components that can occur during the VAN time range, including the N170 and N2pc, adds an additional complication to isolating and identifying the VAN [9]. For example, one experiment failed to detect a bilateral VAN for lateralized moving stimuli; however, while analyzing contralateral versus ipsilateral activity to measure the N2pc, they did, in fact, find a significant negative difference correlating with conscious motion perception in the 200–300-ms time range, but only at electrode sites contralateral to the moving stimulus [91]. Had they specifically calculated the difference in neural activity between conscious and unconscious trials for contralateral electrodes only, a significant VAN would have been found (Figure 2).

The single study using non-lateralized stimuli that failed to observe a VAN reported that an 'N170' correlated with awareness of faces, while the VAN was absent [93]. However, the authors used only face stimuli in their paradigm, making it difficult to isolate the N170, which is defined as a difference between face and non-face stimuli [94]. Instead, they analyzed the difference between seen versus unseen faces in the N170 time range, meaning that the resulting neural difference could have contained an N170, a VAN, or a combination of both.

Although it must be acknowledged that research on the AAN is limited compared with the plethora of studies on the VAN, a growing body of work indicates that the AAN is a true correlate of auditory consciousness [31,33,47,68,75,76,80,83,95,96]. Indeed, the AAN has even been observed in trials during which the subject erroneously reports hearing snippets of speech in the presence of pure noise (i.e., during a hallucination [97]). Only a single experiment investigating the AAN failed to detect it, using a complex design in which participants had to detect a target that was defined as a sequence of two repeated tones within a multitone background [98]. An AAN-like negativity correlated with awareness only in response to the second tone in the target pair but not the first, which the authors interpret as being indicative of the 'AAN' reflecting the process of segregating an auditory stimulus from a multitone background rather than consciously perceiving the stimulus. Critically, however, the target could be consciously identified only after both tones had been played. Accordingly, no neural activity related to target detection should be observed for the first tone, because, while perception of the first tone is a prerequisite for target detection, it is not sufficient. Thus, their findings cannot be considered firm evidence against the AAN being a true NCC,

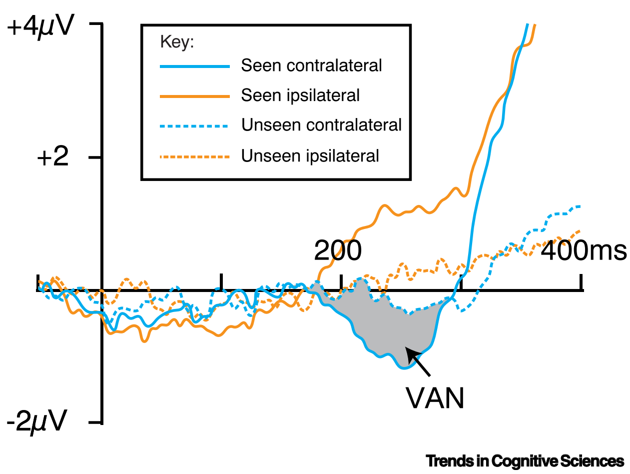

Figure 2. Contralateral and ipsilateral event-related potential (ERP) waveforms in a motion detection task evoked by seen and unseen lateralized visual stimuli. While no significant difference in activity between contralateral and ipsilateral stimuli was present when the lateralized stimuli were unseen (broken traces), a significant negative difference [i.e., visual awareness negativity (VAN)] emerges between the seen and unseen contralateral conditions (unbroken blue versus broken blue waveforms, 200–300 ms). Pooling contralateral and ipsilateral data cancels out this seen–unseen difference. Adapted from Figure 4a in [91].

although more research is necessary to clarify whether the AAN might be more reflective of conscious perception of auditory streams rather than single tones under certain circumstances [95,99].

Taken together, the studies discussed earlier that reported an absence of VAN or AAN when contrasting neural signals elicited by perceived versus non-perceived stimuli fail to present a significant challenge to the hypothesis that the VAN and AAN are true NCC. As such, these neural signals remain the most promising neural correlates of conscious perception to date.

Perceptual awareness negativity: a generalized marker of conscious perception?

The identification of similar markers of consciously seeing and hearing begs the question of whether analogous neural signals might correlate with stimulus consciousness in other modalities. Indeed, mounting evidence indicates the existence of a somatosensory counterpart to the VAN and AAN known as the N140 [100], here referred to as the somatosensory awareness negativity (SAN). The SAN is a negative-going somatosensory-evoked potential with a peak latency of approximately 120–180 ms, a frontal topography contralateral to the stimulated body part [45,69,100–102], and, like the VAN and AAN, is robust to task manipulations [103].

The VAN, AAN, and SAN share a striking number of similarities, including their latency, polarity, lateralization, and location above associated sensory cortices, raising the possibility that similar underlying neural processes may support consciousness across different modalities (Figure 3 and Table 1). Although their topographies are distinct (the VAN is maximal over posterior, occipital-parietal areas [81,104], while the AAN and SAN are strongest over more anterior, lateral regions [33,100]), they match the expected topographies of signals originating from their respective sensory cortical areas.

Indeed, source localization, complemented by structural and functional MRI data, implicate the sensory cortices as the primary generators of the three neural signals: the VAN has been consistently localized to occipital and inferotemporal regions, corresponding to low and mid-level visual cortices within the 'ventral visual stream' [61,87,88,105–107]; the AAN has been localized to the auditory cortex and surrounding regions [31,47,75,76,96]; and the SAN has been localized to the

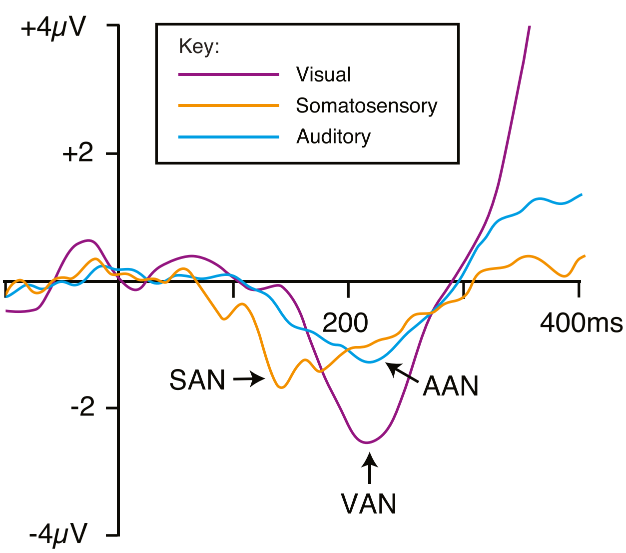

Figure 3. Visual, auditory, and somatosensory awareness negativities. Difference waves between conscious and unconscious trials in detection tasks using visual, auditory, or somatosensory stimuli recorded from the maximal scalp site(s) for each respective sensory modality; visual awareness negativity (VAN), averaged over occipital electrodes; auditory awareness negativity (AAN), averaged across Fz and Cz electrodes; somatosensory awareness negativity (SAN), electrode C6. Waveforms are based on Figure 3 (O) from [29] (VAN), Figure 3 (left) from [33] (AAN), and Figure 2b from [100] (SAN).

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Table 1. Latencies and topographies of the VAN, AAN, and SAN[a]

	VAN	AAN	SAN
Time window	170–290 ms	130–230 ms	125–180 ms
Average peak latency	230 ms	180 ms	140 ms
Topography	Occipital	Fronto-central	Fronto-central

[a]Data are derived from 16 VAN [27,29,58–60,62,64,67,81,82,85,87,89,104,106,135], nine AAN [31,33,68,75,76,80,96,136,137], and five SAN [45,100,108,138,139] published studies.

primary and secondary somatosensory cortices [45,108–110]. Finally, the VAN, AAN, and SAN are conspicuously absent or highly attenuated in right-brain-damaged patients who are unable to perceive stimuli in the left hemifield due to multimodal hemi-spatial neglect; furthermore, these neural signals reappear and normalize as neglect symptoms improve [109].

These converging findings point to the existence of a generalized but modality-specific electrophysiological marker of the onset of sensory consciousness, robust to variation in task relevance or response requirements. We term this a generalized perceptual awareness negativity or PAN, a negative-going neural signal beginning between 120–200 ms following the onset of a consciously perceived visual, auditory, or tactile stimulus (Table 1).

Concluding remarks

The identification of the PAN suggests that similar neural processes might underly consciousness across sensory domains, with unique cortical sources depending on the modality but a shared functional structure. If so, these common mechanisms related to the onset of conscious perception [78] might be isolated from processes specific to each modality to reveal generalized patterns of neural circuit activity related to perceptual consciousness across sensory domains. Future research using both noninvasive EEG and MEG in humans as well as invasive techniques in animals and human patients undergoing neurosurgery will be necessary to identify the physiological mechanisms responsible for generating the PAN [111], dissect its circuit and neuronal constituents [78,112], pursue its neuronal sequela, and address a host of outstanding questions (see Outstanding questions).

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Declaration of interests

No interests are declared.

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Outstanding questions

Does the PAN extend to olfaction, gustation, interoceptive sensation, pain, and linguistic processing?

Does the PAN correlate with stimulus consciousness on a trial-to-trial level or just on average?

How do stimulus salience (e.g., stimulus energy, contrast), stimulus duration (i.e., is the PAN associated with the onset or with the duration of stimulus consciousness?), and levels of processing (e.g., low-level feature detection, such as line orientation or color, versus high-level identification, such as word and face recognition) affect the latency, topography, and amplitude of the PAN?

How do expectations and task relevance modulate the PAN?

Can the PAN be elicited when bypassing peripheral receptors (e.g., by direct brain stimulation, recall, imagery, or during dreams)?

Is the PAN absent during anesthesia and during dream-less sleep?

How does selective attention (and the associated negativities) interact with the PAN?

Can a standard paradigm for eliciting the PAN be developed for use in patients with disorders of consciousness?

What is the significance of the PAN to multimodal integration, binding, and other crossmodal interactions?

Can a PAN be elicited in either hemisphere of split-brain patients?

Does the PAN originate in primary or in higher-order sensory cortical regions? Does it depend on input from prefrontal regions?

Can a PAN be elicited in non-human primates and in rodents? This would permit its circuit and subcellular biophysical origins to be experimentally addressed.

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