Interactive report

Attentional control of the processing of neutral and emotional stimuli

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Abstract

A typical scene contains many different objects that compete for neural representation due to the limited processing capacity of the visual system. At the neural level, competition among multiple stimuli is evidenced by the mutual suppression of their visually evoked responses and occurs most strongly at the level of the receptive field. The competition among multiple objects can be biased by both bottom-up sensory-driven mechanisms and top-down influences, such as selective attention. Functional brain imaging studies reveal that biasing signals due to selective attention can modulate neural activity in visual cortex not only in the presence but also in the absence of visual stimulation. Although the competition among stimuli for representation is ultimately resolved within visual cortex, the source of top-down biasing signals likely derives from a distributed network of areas in frontal and parietal cortex. Competition suggests that once attentional resources are depleted, no further processing is possible. Yet, existing data suggest that emotional stimuli activate brain regions ‘automatically,’ largely immune from attentional control. We tested the alternative possibility, namely, that the neural processing of stimuli with emotional content is not automatic and instead requires some degree of attention. Our results revealed that, contrary to the prevailing view, all brain regions responding differentially to emotional faces, including the amygdala, did so only when sufficient attentional resources were available to process the faces. Thus, similar to the processing of other stimulus categories, the processing of facial expression is under top-down control.

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1. Introduction

As memorably put by William James, attention allows “possession of the mind, in clear and vivid form, of one out of what seems several simultaneously possible objects or trains of thought. Focalization, concentration of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others” [38] (p. 403). Since the time of James, we have greatly advanced his penetrating insights and now have a fairly good understanding of how attention modulates brain processes, as revealed by the recording of single-cell activity, event-related potentials, and hemodynamic events in neuroimaging studies. Although the regions affected by attention have been extensively studied in the past decade, much less is known about the brain areas that control attention. The areas that express the effects of attention are typically sensory processing areas (e.g. visual cortex). By contrast, the areas that control this expression appear to be prefrontal and parietal regions. However, less is known about the mechanisms by which these regions control the flow of processing within the regions affected by attention.

Because processing capacity is limited, selective attention to one part of the visual field comes at the cost of neglecting other parts. Thus, several investigators have proposed that there is competition for neural resources [7,20–23,32,34]. In the present paper, we will adopt the framework advanced by the biased competition model of attention, as developed by Desimone and Duncan [21]. According to this model, illustrated in Fig. 1, the competi-
stimuli undergo competition for neural resources, as do neutral ones, or whether they comprise a special category of stimuli that may be processed ‘automatically’.

2. Biased competition model of attention

2.1. Sensory interactions among multiple visual stimuli

What are the neural correlates for competitive interactions among multiple objects in the visual field? Single-cell recording studies in the monkey have shed light on this question by comparing responses to a single visual stimulus presented alone in a neuron’s receptive field (RF) with the responses to the same stimulus when a second one is presented simultaneously within the same RF [67,85]. When the monkey attended to stimulus outside the RF, it has been shown that the responses to the paired stimuli within the RF were a weighted average of the responses to the individual stimuli when presented alone. For example, if a single effective stimulus elicited a high firing rate and a single ineffective stimulus elicited a low firing rate, the response to the paired stimuli was reduced compared to that elicited by the single effective stimulus. This result indicates that two stimuli present at the same time within a neuron’s RF are not processed independently, for, if they were, then the responses to the two stimuli when presented together would have summed. Rather, the reduced response to the paired stimuli suggests that the two stimuli within the RF interacted with each other in a mutually suppressive way. This sensory suppressive interaction among multiple stimuli has been interpreted as an expression of competition for neural representation. Sensory suppression among multiple stimuli present at the same time in the visual field has been found in several areas of the visual cortex, including extrastriate areas V2, V4, the middle temporal (MT) and medial superior temporal (MST) areas, and the inferior temporal cortex [63,67,81,85,87,91].

Based on hypotheses derived from these monkey physiology studies, we examined competitive interactions among multiple stimuli in the human cortex using functional magnetic resonance imaging (fMRI) [42]. In these studies, hemodynamic changes, as measured by fMRI, were used as indirect measures of neural activity [4,49,72]. Complex, colorful visual stimuli, known to evoke robust responses in ventral stream visual areas of the monkey brain, were presented eccentrically in four nearby locations of the upper right quadrant of the visual field, while subjects maintained fixation. Fixation was ensured by having subjects count the occurrences of Ts or Ls at fixation in a stream of Ts and Ls, an attentionally demanding task. The stimuli were presented under two different presentation conditions, sequential and simultaneous. In the sequential presentation condition (Fig. 2A), a
single stimulus appeared in one of the four locations, then another appeared in a different location, and so on, until each of the four stimuli had been presented in the four different locations. In the simultaneous presentation condition (Fig. 2B), the same four stimuli appeared in the same four locations, but they were presented together. Thus, integrated over time, the physical stimulation parameters were identical in each of the four locations in the two presentation conditions. However, sensory suppression among stimuli within RFs could take place only in the simultaneous, not in the sequential presentation condition.

Sequential and simultaneous conditions were presented in blocks interleaved with blank periods, during which time subjects continued to count the occurrences of Ts or Ls but no stimuli were presented. As predicted by our hypothesis that stimuli presented together interact in a mutually suppressive way, simultaneous presentations evoked weaker responses than sequential presentations in all activated visual areas, which included V1, V2, V4, TEO, V3A and the MT complex (hereafter called area MT). This is illustrated for V2 and V4 in Fig. 3A. Importantly, the difference in activations between sequential and simultaneous presentations was smallest in V1 and increased in magnitude towards ventral extrastriate areas V4 (Fig. 3A) and TEO, and dorsal extrastriate areas V3A and MT. This increase in magnitude of the sensory suppressive effects across visual areas suggests that the sensory interactions were scaled to the increase in RF size of neurons within these areas. That is, the small RFs of neurons in V1 and V2 would encompass only a small portion of the visual display, whereas the larger RFs of neurons in V4, TEO, V3A and MT would encompass all four stimuli. Therefore, suppressive interactions among the stimuli within RFs could take place most effectively in these more anterior extrastriate visual areas (see also [43]).

2.2. Attention biases competition: filtering of unwanted information

Single-cell recording studies in the monkey have demonstrated that spatially directed attention can bias the competition among multiple stimuli in favor of one of the stimuli by modulating competitive interactions. In particular, in extrastriate areas V2 and V4 it has been shown that spatially directed attention to an effective stimulus within a neuron’s RF eliminates the suppressive influence of a second, ineffective stimulus presented within the same RF. For example, if attention is directed to the effective stimulus, it is as if the ineffective stimulus were not in the RF. When a monkey directs attention to one of two competing stimuli within a RF, the response is similar to the response to that stimulus presented alone [85]. These findings imply that attention may resolve the competition among multiple stimuli by counteracting the suppressive influences of nearby stimuli, thereby enhancing information processing at the attended location. This may be an important mechanism by which attention filters out unwanted information from cluttered visual scenes [20,21].

Our recent fMRI studies suggest that a similar mechanism operates in the human visual cortex [42]. We studied the effects of spatially directed attention on multiple competing visual stimuli in a variation of the paradigm we used to examine competitive interactions among simultaneously presented stimuli, described above. In addition to the two different visual presentation conditions, sequential and simultaneous (Fig. 2), two different attentional con-
Fig. 3. Sensory suppression and attentional modulation in human visual cortex. (A) Sensory suppression in V2 and V4. As shown by the time series of fMRI signals, simultaneously presented stimuli (SIM) evoked less activity than sequentially presented stimuli (SEQ). (B) Attentional modulation of sensory suppression. The sensory suppression effect was replicated in the unattended condition of this experiment, when the subjects’ attention was directed away from the stimulus display (unshaded time series). Spatially directed attention (blue shaded time series) increased responses to simultaneously presented stimuli to a larger degree than to sequentially presented ones (see arrows).

ditions were tested, such that the eccentrically presented stimuli were either unattended or attended. During the unattended condition, attention was directed away from the visual display by having subjects count Ts or Ls at fixation, exactly as in our original study. In the attended condition, subjects were instructed to maintain fixation and attend covertly to the peripheral stimulus location closest to fixation in the display and to count the occurrences of one of the four stimuli presented there, which was indicated before the scan started.

The same areas in striate and extrastriate cortex were activated during both the unattended and attended condition, namely, V1, V2, V4, TEO, V3A, and MT. However, in the attended condition, the extent of activation increased significantly in V4, TEO, V3A, and MT. As illustrated in Fig. 3B, for area V4, directing attention to the location closest to fixation in the display enhanced responses to both the sequentially and the simultaneously presented stimuli. More importantly, and in accordance with our prediction from monkey physiology, directed attention led to greater increases of fMRI signals to simultaneously presented stimuli than to sequentially presented stimuli. Additionally, the magnitude of the attentional effect scaled with the magnitude of the suppressive interactions among stimuli, with the strongest reduction of suppression occurring in ventral extrastriate areas V4 (Fig. 3B) and TEO, suggesting that the effects scaled with RF size. These findings support the idea that directed attention enhances information processing of stimuli at the attended location by counteracting suppression induced by nearby stimuli, which compete for limited processing resources. In essence, unwanted distracting information is effectively filtered out.

3. Top-down attentional control

In humans, studies of patients suffering from attentional deficits due to brain damage, as well as functional brain imaging studies of healthy individuals performing attentionally demanding tasks, have given insights into a distributed network of higher-order areas in frontal and parietal cortex that appears to be involved in the generation and control of attentional top-down feedback signals, as proposed by the biased competition model. Furthermore, there exists an anatomical substrate for such top-down influences (Fig. 4), inasmuch as tract-tracing studies in monkeys have demonstrated direct feedback projections to
form a distributed network for spatially directed attention [62,78].

3.2. Functional brain imaging studies

3.2.1. Meta-analysis

Neuroimaging studies of visual attention have helped to elucidate how the processing of visual information is enhanced for attended compared to unattended information. In addition to examining activations within visual cortex, it is also informative to examine whether other brain regions are routinely recruited by attentional tasks. Interestingly, a fronto-parietal network of regions consisting of areas in the superior parietal lobule (SPL), the frontal eye field (FEF), and the supplementary eye field (SEF) has been consistently activated in a variety of tasks involving visuospatial attention [12,15,16,26,29,48,71,88,100]. In addition, but less consistently, activations in the inferior parietal lobule (IPL), the lateral prefrontal cortex (PFC), as well as indirect feedback projections to areas V4 and TEO from prefrontal cortex via parietal cortex [9,98,105].

3.1. Lesion studies

Lesions of the right cerebral hemisphere may produce the syndrome of visuospatial neglect: although visual sensation is intact, patients fail to detect stimuli in the side of space opposite the lesion, and they are not consciously aware of contralesional objects or parts of objects [62,80]. For example, a patient will read from one side of a book, apply make-up to only one half of her face, or eat from only one side of a plate. Patients with visuospatial neglect typically exhibit extinction. Detection reaction time in the contralesional field is not significantly slowed if a valid cue is given. When, however, a cue draws attention to the ipsilesional field and the target subsequently appears in the opposite, contralesional field, then detection time is slowed dramatically. This pattern of results (i.e. extinction) is often interpreted as a deficit in one of the proposed elementary operations of attention [78], namely, disengagement.

Visuospatial neglect may follow unilateral lesions at very different sites, including the parietal lobe, especially its inferior part and the temporo-parietal junction [99], regions of the frontal lobe [17,36], the anterior cingulate cortex [39], the basal ganglia [17] and the thalamus, in particular, the pulvinar [104]. Studies in monkeys have implicated the same brain regions [28,53,61,77,103,108]. The finding that lesions of many different areas may cause visuospatial neglect has led to the notion that these areas form a distributed network for spatially directed attention [62,78].

3.2.2. Isolating ‘cue’ and ‘target’ activity

The approach of analyzing the cortical response to a cue as a tool to study control mechanisms of visuospatial attention was first used in event-related potentials by Harter and colleagues [33a]. Subsequently, neuroimaging studies of visual attention used a similar approach to elucidate how the processing of visual information is increased for attended compared to unattended information (e.g. Ref. [14]). In many of these studies, however, it was not possible to separate signals associated with visual cues that prime the subject to expect potential subsequent visual targets from signals associated with the attended targets themselves, because cues and targets follow each other in rapid succession. More recent neuroimaging studies, however, have attempted to explicitly investigate top-down modulation in attentional paradigms by disentangling cue- and target-related activity by, for instance, introducing a longer interval between the two [35,44]. In this way, the effects of attention in the presence and in the absence of visual stimulation can be assessed. The reasoning is that purely target-related activity should be observed in visual processing areas that respond to the specific stimulus (e.g. MT to moving stimuli). At the same time, expectation- or
Fig. 5. Meta-analysis of studies investigating the spatial attention network. Talairach (peak) coordinates of activated areas in parietal and frontal cortex from the following studies are indicated: (1) Corbetta et al. (1993) [15]; (2) Fink et al. (1997) [26]; (3) Nobre et al. (1997) [71]; (4) Vandenbergh et al. (1997) [100]; (5) Corbetta et al. (1998) [12]; (6) Culham et al. (1998) [16]; (7) Kastner et al. (1999) [42]; (8) Rosen et al. (1999) [88]; (9) Corbetta et al. (2000) [13]; (10) Hopfinger et al. (2000) [37]. Abbreviations: ACC, anterior cingulate cortex; FEF, frontal eye field; IPS, intraparietal sulcus; MFG, middle frontal gyrus; SEF, supplementary eye field; SPL, superior parietal lobule. Based on Kastner and Ungerleider [46].

cue-related activity that is uncontaminated by ensuing target-related activity should reflect mainly top-down signals and be observed in attentional control regions of the brain. We will next describe one of our studies and then review a few related ones.

We explored attentional biasing signals in the human visual cortex in the absence of visual stimulation by adding a third experimental condition to the design used to investigate competitive interactions and their modulation by attention [44]. In addition to the two visual presentation conditions, sequential and simultaneous, and the two attentional conditions, unattended and attended, an expectation period preceding the attended presentations was introduced. The expectation period was initiated by a marker (the cue) presented briefly next to the fixation point 11 s before the onset of the stimuli. At the appearance of the marker, subjects covertly shifted attention to the peripheral target location in anticipation of a target stimulus that would appear there. In this way, the effects of attention in the presence and absence of visual stimulation could be identified (Fig. 6).

Directed attention in the absence of visual stimulation activated the same distributed network of areas as directed attention in the presence of visual stimulation and consisted of the FEF, the SEF, and the SPL. A time course analysis of the fMRI signals revealed that there was an increase in activity in these frontal and parietal areas during the expectation period (in the absence of visual input), with no further increase in activity evoked by the attended stimulus. Rather, there was sustained activity throughout the expectation period and the attended visual presentations. These results suggest that the activity reflected the attentional operations of the task per se and not the effects of attention on visual processing. This conclusion is supported by the finding that, in the unattended condition, no significant visually evoked activity was observed in these frontal and parietal regions.

Additional evidence for a fronto-parietal network of regions involved in attentional control comes from three additional imaging studies. By using a spatial attention Posner-type task, Corbetta et al. [13] showed that the intraparietal sulcus (IPS) was uniquely active when attention was directed toward and maintained at a relevant location (preceding target presentation), suggesting that the IPS is a top-down source of biasing signals observed in visual cortex. The same investigators [92] found, when studying attention to motion, cue-related activity in the intersection of the precentral sulcus and the superior frontal sulcus (likely including the FEF), as well as in several sites in the IPS. Finally, Hopfinger et al. [37] obtained evidence for a wider attentional control network, including the left superior frontal gyrus, bilateral midfrontal gyrus, bilateral SPL, bilateral IPS, as well as bilateral superior temporal gyrus (this latter region was also observed by Corbetta et al. [13]).

Taken together, our study and the ones just cited provide evidence that a distributed fronto-parietal attentional network may be the source of feedback that generates the
top-down biasing signals modulating activity in visual cortex. Because, in our study, the magnitude of the activity in the parietal and frontal areas was comparable during directed attention in the absence and in the presence of visual stimulation, it appears that this activity may be independent of the particular visual task, be it detection or discrimination. This would explain the finding that functional brain imaging studies using different visuospatial attention tasks have described very similar attentional networks. The network revealed by imaging studies exhibits great overlap with the set of regions implicated in visuospatial neglect in studies of patients with brain lesions.

Corbetta and Shulman [15a] have recently proposed two anatomically segregated but interacting networks for spatial attention. According to their scheme, a dorsal fronto-parietal system is involved in the generation of attentional sets associated with goal-directed stimulus–response selection. Key nodes within this largely bilateral network include the IPS/SPL and the FEF. A second, ventral system, which is strongly lateralized to the right hemisphere, is proposed to detect behaviorally relevant stimuli and to work as an alerting mechanism for the first system when these stimuli are detected outside the focus of processing. This latter network is thought to involve the temporo-parietal junction (at the intersection of the inferior parietal lobule and the superior temporal gyrus) and the middle and inferior frontal gyri. Overall, the dorsal and ventral networks can be thought of as subserving, respectively, endogenous and exogenous spatial attention functions. Although previous studies explicitly comparing these two functions revealed largely overlapping networks (e.g. Refs. [48,88], because of the interacting nature of the two networks, more subtle event-related designs may be required to reveal the anatomical specificities of the two systems.

3.2.3. Increases of baseline activity

What is the evidence that the top-down biasing signals generated in frontal and parietal areas produce a change within visual cortex so that visually evoked activity there is enhanced? Single-cell recording studies have shown that spontaneous (baseline) firing rates are 30–40% higher for neurons in areas V2 and V4 when a monkey is cued to attend covertly to a location within the neuron’s RF before the stimulus is presented there; that is, in the absence of visual stimulation [60]. A similar effect was demonstrated in dorsal stream area LIP [11]. This increased baseline activity, termed the ‘baseline shift’, has been interpreted as a direct demonstration of a top-down signal that feeds back from higher-order control areas to lower-order processing areas. In the latter areas, stimuli at attended locations
would be biased to ‘win’ the competition for processing resources at the expense of stimuli appearing at unattended locations [7,20–23,34]. Such a shift in baseline activity would ‘sensitize’ neurons with RFs at the attended location, so that when a stimulus subsequently appeared at that location there would be enhanced visually evoked activity.

In our study in which we introduced an expectation period, described above [44], in addition to the observed frontal and parietal activations, we found that visual processing areas were also activated. This activity was related to directing attention to the target location in the absence of visual stimulation, in anticipation of the target stimulus that would appear there. Notably, the increase in activity during these expectation periods was topographically specific, inasmuch as it was only seen in areas with a representation of the attended spatial location, specifically, in areas V1, V2, V4, and VEO. The increase of baseline activity during the expectation period was followed by a further increase of activity evoked by the onset of the stimulus presentations.

The baseline increases found in human visual cortex [10,44,45,92] may be subserved by increases in spontaneous firing rate similar to those found in the single-cell recording studies [11,60], but summed over large populations of neurons. The increase evoked by directing attention to a target location in anticipation of a behaviorally relevant stimulus at that attended location are thus likely to reflect a top-down feedback bias in favor of the attended location in human visual cortex.

4. Attention and the processing of emotion-laden stimuli

Thus far, we have considered the neural basis for the control of the processing of neutral stimuli, that is, those without emotional valence. But, in addition to neutral stimuli, others can be considered as either positive (associated with appetitive behaviors) or negative (associated with withdrawal behaviors). We now turn to issues raised by studying the processing of visual stimuli with emotional content and, in particular, how stimulus valence and attention interact.

4.1. Is attention necessary for the processing of faces with emotional expression?

To what extent are unattended objects processed by the visual system? Psychophysical evidence suggests that processing outside the focus of attention is attenuated and may even be eliminated under some conditions [54,75]. For example, ‘change blindness’ studies show that subjects may fail to report even very large changes in complex scenes, provided the changes are not associated with stimulus transients that capture attention [84,93]. Even low-level tasks commonly thought to be ‘preattentive’, such as orientation pop-out, may require attention to be successfully performed [41]. Likewise, at the neural level, the stimulus-evoked fMRI response is essentially eliminated when subjects are engaged in a competing task with high attentional load. For example, moving stimuli did not elicit fMRI activation in area MT when subjects performed a concurrent, highly demanding linguistic task [82], and activations associated with words were not observed when subjects performed a concurrent, highly demanding object working memory task [83]. Taken together, these studies suggest that perception and its underlying neural substrate may be abolished if attentional resources are completely consumed by a competing task.

A major exception to this critical role of attention may be the neural processing of emotion-laden stimuli, which are reported to be processed automatically, namely, without attention [73,74,101]. For example, subjects exhibit fast, involuntary autonomic responses to emotional stimuli, such as aversive pictures or faces with fearful expressions [30,109]. Other behavioral studies suggest that the visual processing of facial expression occurs not only automatically [94] but may even take place without conscious awareness [73]. This conclusion is also supported by imaging studies of the neural processing of emotional stimuli in the amygdala, a structure that is known to be important in the processing of emotion, particularly fear [1,51,57]. Such studies report that the amygdala is activated not only when normal subjects view fearful faces, but even when these stimuli are masked and subjects appear to be unaware of their occurrence [69,110]. The view has thus emerged that the amygdala is specialized for the fast detection of emotionally relevant stimuli in the environment, and that this can occur without attention and even without conscious awareness.

In a recent study, we tested the alternative possibility, namely, that the neural processing of stimuli with emotional content is not automatic and instead requires some degree of attention, similar to the processing of other stimulus categories. We hypothesized that the failure to modulate the processing of emotional stimuli by attention in previous studies was due to a failure to fully engage attention by a competing task. In other words, activation in the amygdala by emotional stimuli should resemble activation in MT; if the competing task is of high load, activation should be reduced or absent. We therefore employed fMRI and measured activations in the amygdala and other brain regions that responded differentially to faces with emotional expressions (fearful and happy) compared to neutral faces and then examined how these responses were modulated by attention.

We measured fMRI responses evoked by pictures of faces with fearful, happy, or neutral expressions when attention was focused on them (attended condition), and compared the responses evoked by the same stimuli when attention was directed to oriented bars (unattended condition). In alternating blocks of trials, subjects performed a
gender discrimination task on the faces and a same/different orientation discrimination task on the eccentric bars (Fig. 7). On all trials, subjects fixated centrally on the faces, attending only covertly to the eccentrically presented bars on the unattended trials. In designing our bar orientation task, we chose one that was sufficiently demanding to exhaust all attentional resources on that task and leave little or none available to focus on the faces, even though they were viewed foveally during the bar orientation task. Behavioral performance indicated that the bar orientation task was indeed extremely difficult, inasmuch as subjects were correct only on 64% of the trials.

As shown in previous studies [65,66,73,101,103], fearful faces produced greater activation than neutral faces in the amygdala, as revealed by the analysis of attended trials only; this effect was bilateral. Attended compared to unattended faces evoked significantly greater activations bilaterally for all facial expressions (Fig. 8). Importantly, there was a significant interaction between stimulus valence and attention, that is, in the left amygdala the differential response to stimulus valence was observed only in the attended condition (Fig. 8B); in the right amygdala we observed a trend. For the unattended condition, responses to all stimulus types were equivalent and not significantly different from zero. Thus, amygdala responses to emotional stimuli are not automatic and instead require attention.

Fig. 7. Experimental paradigm to study the interaction of stimulus valence and attention. While subjects fixated the faces, they indicated in alternating blocks of trials, either whether the face was male or female (‘attended’ trials), or whether the bars were or were not of similar orientations (‘unattended’ trials); the dashed lines indicate the display regions attended on alternating blocks (not shown on actual displays). On each trial, the faces were fearful, happy, or neutral. Stimuli are not drawn to scale.

Fig. 8. Attention and valence effects in the amygdala. (A) Arrows point to the amygdala. Attended faces compared to unattended faces evoked significantly greater activations for all facial expressions. The level of the coronal section is indicated on the small whole-brain inset. (B) Estimated responses for the left and right amygdala regions of interest as a function of attention and valence. FA, fearful attended; FU, fearful unattended; HA, happy attended; HU, happy unattended; NA, neutral attended; NU, neutral unattended.
Outside of the amygdala, differential effects of valence as a function of attention were also observed in a number of other brain regions. These regions comprised several visual processing areas, including the calcarine fissure, the middle occipital and fusiform gyri, and the right superior temporal sulcus (STS), as well as the insula, nucleus accumbens, the anterior cingulate gyrus, and orbitofrontal cortex (including ventromedial and orbital territories). As in the amygdala, in these brain regions, enhanced responses to fearful and/or happy faces compared to neutral faces was not automatic but instead required attention.

Our findings are in direct contrast to those by Vuilleumier et al. [101] who also studied the effects of attention and valence on face processing, using a variation of the task used by Wojciulik et al. [112]. Subjects fixated a central cue and matched either two faces or two houses presented eccentrically. In their study, they failed to see evidence that attention modulated responses in the amygdala, regardless of stimulus valence. What is the explanation for their negative findings? The most likely explanation is that the attentional manipulation in the Vuilleumier et al. [101] study was not as effective as ours. For example, behavioral performance for the bar orientation task in our study and house matching in the Vuilleumier et al. [101] study was 64 and 86% correct, respectively, indicating that our competing task was a more demanding one (see Ref. [76] for further discussion).

To summarize, contrary to the prevailing view, we found that all brain regions responding differentially to faces with emotional content, including the amygdala, did so only when sufficient attentional resources were available to process those faces. Indeed, when all attentional resources were consumed by another task, responses to faces were eliminated, consistent with Lavie’s [54] proposal that if the processing load of a target task exhausts available capacity, stimuli irrelevant to that task will not be processed. Therefore, it does not appear that faces with emotional expressions are a ‘privileged’ category of objects immune to the effects of attention. Instead, facial expressions must compete for neural representation, just as neutral stimuli do; this is illustrated within the context of the biased competition model of attention in Fig. 9.

### 4.2. Emotional stimuli can bias competition for processing resources

Although our results indicate that attentional resources are required for processing stimulus valence, they do not imply that humans are unable to respond to potential threats outside the focus of attention or that the amygdala only responds to attended stimuli. Indeed, even ignored items of neutral valence can attract attention and interfere with on-going processing (e.g. Refs. [54,55,102,114]). Moreover, numerous studies have demonstrated that negative stimuli are a more effective source of involuntary interference to on-going tasks than neutral and positive ones [35,97,101,111], and more readily recruit attention [5,24,79,89]. An interesting example comes from the study by Vuilleumier et al. [101], mentioned above, in which it was found that when subjects performed the house-matching task (i.e. the faces were unattended), RTs were slower if the (ignored) faces were fearful than if they were neutral, suggesting that fearful faces recruited attention even when they were task-irrelevant and ignored.

It therefore appears that emotional (especially negative) stimuli can bias the competition for processing resources, such that they are at a competitive advantage compared to neutral stimuli. If so, then just as attention enhances activity within visual cortex to items at attended locations, so too should emotional pictures evoke stronger responses in visual cortex than neutral ones. This is indeed the case. We and others have found that both posterior, visual processing areas, such as the occipital gyrus, and more anterior, ventral temporal regions, such as the fusiform gyrus, exhibit differential activation when emotional and neutral pictures are contrasted [6,50,52,66,69,96]. In our study of the processing of facial expressions, we observed evidence for emotional modulation such that emotional compared to neutral stimuli produced greater activation throughout ventral occipitotemporal cortex. Remarkably, we also obtained evidence for emotional modulation of activity in and around the calcarine fissure (V1/V2). It therefore appears that, like attentional modulation of activity in visual cortex, emotional modulation can extend to very early processing areas.

In sum, just as attention can favor the processing of attended items, so too does emotional valence. Attended items are associated with faster reaction times and with increased neural activity. In a similar fashion, the processing of emotion-laden stimuli is prioritized and leads to stronger activation in visual processing regions. Thus, we hypothesize that the increased activation produced by emotional stimuli reflects processes of emotional modulation by which the processing of this stimulus category is favored as compared to the processing of neutral stimuli.

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**Fig. 9.** Biased competition model of visual attention and the processing of emotion-laden stimuli. Facial expressions must compete for neural representation (see arrow labeled ‘stimulus valence’), just as neutral stimuli do.
4.3. What is the source of the biasing signal for emotional stimuli?

In the past decade or so, the amygdala has been shown to be a critical node in a circuit mediating the processing of stimulus valence, notably fear. Because of its widespread projections to cortical sensory processing areas, including direct inputs to visual cortical areas as far back as V1 [2], it has been suggested that the amygdala may be the source of modulation of activity evoked by emotional stimuli. Morris et al. [70] found that amygdala signals covary with signals from visual areas in a condition-dependent manner. Such changes in ‘functional connectivity’ highlight changes in the coupling between brain regions. In their study, the correlation between amygdala and visual cortical activity increased when subjects viewed fearful faces compared to happy ones (see also Ref. [90]). Similar findings have been observed when subjects view unpleasant compared to neutral words [95].

In our study of processing of facial expressions, we also examined the coupling between amygdala activity and activity in other brain regions. We anticipated that ventral occipitotemporal cortex would show increased coupling with the amygdala during attended compared to unattended trials. The results of this analysis indeed revealed that the middle occipital and the fusiform gyri exhibited increased coupling with the amygdala on attended trials, a finding consistent with a modulatory role for the amygdala. Fig. 10 illustrates the site of the fusiform enhanced coupling and, for comparison, at the same slice level, the contrast of fearful and neutral faces during attended trials, as this modulation is hypothesized to originate in the amygdala. Note the striking similarity between the two maps. Interestingly, we also found increased coupling between the amygdala with the calcarine fissure on attended trials, which is consistent with projections to very early visual areas, including V1 and V2, from the amygdala (ref).

Increased coupling with the amygdala was not restricted to occipitotemporal regions, but also included the STS, the ventromedial prefrontal cortex and the orbitofrontal cortex, as well as parietal and other frontal regions. While the results from our study and others are thus consistent with a modulatory role for the amygdala, the type of analysis employed (based on activity covariation) cannot determine the direction of the interaction. Therefore, the evidence cited above must be considered indirect.

More direct evidence that the amygdala is a source of emotional modulation comes from a recent study by Anderson and Phelps [3], who showed that patients with bilateral amygdala lesions did not show an advantage at detecting word stimuli with aversive content compared to neutral content, in stark contrast to the behavior of normal subjects. The authors thus suggested that signals originating in the amygdala might help increase perceptual sensitivity to these stimuli. In other words, the amygdala would bias the processing of visual stimuli in favor of ones with valence, which could potentially signal important events in the environment.

Emotional modulation can potentially be implemented in one of two ways. First, it could rely on the direct feedback projections from the amygdala to visual processing areas [2], as illustrated in Fig. 11. Alternatively, the amygdala could modulate activity within these processing areas via its projections to frontal sites that control the allocation of attentional resources. One such site is the dorsolateral prefrontal cortex [2] along the middle frontal gyrus, which is involved in attentional processes (e.g. see axial slice at

![Fig. 10. Coupling of activity between the amygdala and other brain regions. (A) Increases in the coupling between amygdala and visual cortical activity (V1/V2 and fusiform gyrus; see arrows) on attended compared to unattended trials. (B) Contrast of fearful and neutral faces during attended trials, demonstrating a significant effect of valence in the fusiform gyrus. A threshold of $P<0.00001$ (uncorrected) was employed for both A and B (which show the $y=-52$ plane).](image)

![Fig. 11. Emotional modulation. The amygdala receives highly processed visual input from inferior temporal areas TEO and TE. At the same time, the amygdala projects to several levels of visual processing, including as early as V1, which allows it to influence visual processing according to the valence of the stimulus. Note that the amygdala is also interconnected with, among other regions, the orbitofrontal cortex, another brain structure important for the processing of ‘stimulus significance.’ Brain regions: green=occipitotemporal visual processing areas; orange=middle occipital and the fusiform gyrus; red=amygdala (note that the amygdala is not visible from a lateral view of the brain; instead it is situated subcortically near the brain’s medial surface); blue=orbitofrontal cortex (note that important orbitofrontal regions are situated along the midline, and hence are not visible from a lateral view of the brain).](image)
and has recently been shown to integrate cognitive and emotional information [31]. Another site is the rostral anterior cingulate cortex, which has been proposed to be an affective division of the anterior cingulate cortex [8]. The cingulate cortex is proposed to integrate inputs from various sources and to contribute to the modulation of processing in other brain regions [8]; see Ref. [113] for a different proposal. Of course, the possibilities of direct and indirect emotional modulation are not mutually exclusive. Finally, although we have emphasized the role of the amygdala in the attribution of stimulus valence, several brain regions, including the orbitofrontal and ventromedial prefrontal cortices, might act in concert with the amygdala in determining the behavioral and social significance of incoming stimuli. Thus, these frontal regions may be additional sources of emotional modulation.

4.4. How does visual information reach the amygdala: slow-cortical and fast-subcortical pathways for the processing of emotional stimuli

If the amygdala conveys valence to sensory stimuli, what is the pathway by which it receives its sensory inputs? There is evidence that two pathways exist. One of them involves the cortical pathway that starts at early sensory regions, progresses through several intermediate stages, and finally delivers highly processed sensory information to the amygdala. For example, for the visual system, signals reach V1 and proceed through a series of occipitotemporal regions, culminating in projections from inferior temporal area TE to the amygdala [2]. A similar organization is presumed to exist for other sensory systems; for evidence concerning the somatosensory system, see Ref. [27].

The existence of a parallel, subcortical pathway to the amygdala for auditory processing has been demonstrated in studies of fear conditioning to acoustic stimuli in rats and guinea pigs [56,106]. It has been shown, for instance, that the medial geniculate body has direct projections to the amygdala [59], and that interruption of these connections interferes with conditioning (see Ref. [58]). It has thus been proposed that, in general, acoustic signals are transmitted via a ‘fast,’ subcortical route, in addition to the ‘well processed’ signals that the amygdala receives via cortical projections [57].

Several investigators have proposed that a fast, subcortical pathway also exists for the processing of visual stimuli, and, in particular, the processing of face stimuli [18,19,70,73]. This view is supported by studies that, as mentioned above, suggest that the processing of facial expression occurs not only ‘automatically,’ but even without conscious awareness. Based on behavioral and imaging results, Morris et al. [70] have proposed that a retino-collicular–pulvinar–amygdala pathway provides the neural substrate for the automatic processing of facial expression. Recently, affective blindsight (see below) has also been taken as evidence for the subcortical processing of faces.

However, as stated by Vuilleumier et al. [101], a truly automatic pathway should not depend on attentional resources. Yet, in our study, we found a strong interaction between stimulus valence and attention, such that differential responses to emotional and neutral faces only occurred when subjects attended to the faces. Moreover, our results provide strong evidence that both occipitotemporal and amygdala responses were eliminated when processing resources were exhausted. In fact, it is unclear how a proposed subcortical pathway would support the processing of the detailed form information required for face perception. For example, the responses of superior colliculus neurons are unable to discriminate the high spatial resolutions demonstrated by responses of neurons in the geniculostriate system [64,86].

And yet, studies with blindsight patient GY (who has a right hemianopia following left occipital lobe damage) reveal that he is able to discriminate emotional facial expressions presented in his blind hemifield [18,19], a phenomenon called affective blindsight [18]. Moreover, in a recent fMRI study, amygdala responses were elicited in GY to the presentation of fearful and fear-conditioned faces in his blind hemifield [68], suggesting that information reached the amygdala subcortically. One difficulty with the interpretation of GY’s results is that he suffered an occipital lesion at an early age (8 years old), which may have produced experience-dependent changes in collicular function. Experiments with monkeys indicate that the number of collicular cells with enhanced responses to visual targets increases significantly following striate cortex lesions [65]. According to Morris et al. [68], similar plasticity in GY’s superior colliculus may explain the gradual improvements in his blindsight performance that have been observed during repeated testing over the years [107]. Other possible, and less interesting, explanations for GY’s discrimination of facial expressions could involve improper fixation and residual vision in his ‘blind’ hemifield [25].

Based on the findings reviewed above and our own study, we suggest that in the normal brain the critical pathway for the processing of facial expressions is not subcortical but rather proceeds from V1 to extrastriate areas, including the fusiform gyrus and STS, and then to the amygdala. If attentional resources are depleted, however, face stimuli, regardless of valence, will fail to reach the amygdala and will fail to be tagged with emotional expression. Consequently, valence information will not be conveyed. This is exactly what we observed when subjects were engaged in a high-load, competing task: neither the amygdala nor regions to which it projects showed a valence effect. Thus, contrary to simple auditory stimuli, for which subcortical processing is likely to be sufficient, for detailed form information required for face perception,
a cortical pathway seems to be necessary. In fact, there is evidence that in conditioning paradigms involving finer acoustic discrimination, where one conditioned stimulus is paired with shock and another is not, cortical lesions interfere with conditioning [40].

Thus, according to our proposal, the initial volley of activation over occipitotemporal cortex when emotional faces are viewed would be equivalent to that produced by neutral faces. Later, after feedback from other structures such as the amygdala converge onto occipitotemporal cortex, the responses would be selective for the valence of the stimulus. This view is consistent with results from event-related potential studies, which reveal that valence-modulated components in occipitotemporal cortex occur between 250 and 600 ms after stimulus onset, far exceeding the so-called N170 face-selective responses (170 ms post stimulus).

4.5. Attention and awareness

We have proposed that attention is required for the expression of valence. How does one reconcile this view with the finding that amygdala responses are evoked by masked faces of which subjects are presumably unaware [69,110]? In such instances, it is possible that attentional resources to the masked stimuli were not sufficiently reduced by a competing task. Typically, in masking paradigms subjects are required to direct attention to the location of the stimulus in the absence of any competing task, suggesting that attentional resources are available to allow for subliminal responses to the emotional stimuli. Thus, while attention appears to be necessary for the processing of faces with emotional expressions, it may not ensure that they reach awareness.

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