Social vision: Sustained perceptual enhancement of affective facial cues in social anxiety

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ABSTRACT

Heightened perception of facial cues is at the core of many theories of social behavior and its disorders. In the present study, we continuously measured electrocortical dynamics in human visual cortex, as evoked by happy, neutral, fearful, and angry faces. Thirty-seven participants endorsing high versus low generalized social anxiety (upper and lower tertiles of 2104 screened undergraduates) viewed naturalistic faces flickering at 17.5 Hz to evoke steady-state visual evoked potentials (ssVEPs), recorded from 129 scalp electrodes. Electrophysiological data were evaluated in the time-frequency domain after linear source space projection using the minimum norm method. Source estimation indicated an early visual cortical origin of the face-evoked ssVEP, which showed sustained amplitude enhancement for emotional expressions specifically in individuals with pervasive social anxiety. Participants in the low symptom group showed no such sensitivity, and a correlational analysis across the entire sample revealed a strong relationship between self-reported interpersonal anxiety/avoidance and enhanced visual cortical response amplitude for emotional, versus neutral expressions. This pattern was maintained across the 3500 ms viewing epoch, suggesting that temporally sustained, heightened perceptual bias towards affective facial cues is associated with generalized social anxiety.

Introduction

Attentional biases that subserve an intense apprehension of interpersonal scrutiny and negative evaluation have been proposed to underlie social phobia, in particular the generalized subtype (Hofmann et al., 2004; Rosenberg et al., 2009). To test perceptual hypersensitivity to social threat cues in socially anxious individuals, static facial expressions have often been presented and much of the data has been interpreted in accordance with the vigilance-avoidance hypothesis—that perception of threat-relevant stimuli in anxious individuals is characterized by initial hypervigilance and consequent defensive avoidance (Mogg et al., 1997). For example, the dot-probe paradigm entails a spatial cueing procedure in which participants make a speeded response to a probe (e.g., a letter) when it replaces a cue in the same visual hemifield (e.g., angry face) after approximately 500 to 1000 ms. Typically, response latencies to hemifield probes are reduced when preceded by fear-relevant (angry or disgusted faces) as opposed to neutral cues and this pattern is enhanced with social anxiety and interpreted as evidence of early hypervigilance (Amir et al., 2009; Klumpp and Amir, 2009; Mogg and Bradley, 2002; Mogg et al., 2004; Pishyar et al., 2004). Although the dot-probe task has

yielded compelling results implicating altered spatial attention to facial displays in social anxiety it is difficult to disentangle attentional effects such as facilitation to versus impaired disengagement from fear-relevant stimuli (Bögels and Mansell, 2004; Mogg et al., 1997). Furthermore, discrete reaction times represent the outcome of a cascade of perceptual processes as well as explicit decision-making and speeded motor responses.

More temporal information about orienting in social anxiety has been revealed via eye-tracking methodology. When pairs of computer-generated faces are presented, high compared to low socially anxious individuals more often fixate initially on the angry or happy relative to neutral face (Wieser et al., 2009b) and show impairments when directed to inhibit reflexive orienting towards emotional as well as neutral expressions (Wieser et al., 2009a). Horley et al. (2003, 2004) found that over the course of prolonged presentations (i.e., 10 s) of single facial expressions social phobia patients relative to controls demonstrated increased scanning over the face coupled with reduced fixations on the eyes, a pattern accentuated in response to aversive facial displays. Overall, emerging oculomotor data suggest that social phobia is associated with biased orienting to facial displays, especially those connoting interpersonal threat. However, it should be noted that these findings do not inform on covert shifts of attention or other aspects of the fear response (e.g., physiological arousal). Furthermore, disengagement or perceptual avoidance of viewed stimuli is difficult to quantify due to the involvement of several saccades (Garner et al., 2006; Mogg et al., 1997).

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As electrophysiological techniques are sensitive to covert attention processes and provide continuous measures of attention fluctuations easily related to behavioral (Ihssen et al., 2007; Keil and Heim, 2009), oculomotor (Müller et al., 2008), probe reflex (Löw et al., 2008; Schupp et al., 1997) and autonomic (Keil et al., 2008; Moratti et al., 2006) measures they can productively complement the aforementioned studies of social anxiety. Primarily utilizing event-related potentials (ERPs) obtained by means of time-domain averaging multiple segments of electrocortical activity, investigators have assessed attentional allocation to facial expressions over a wide range of exposure durations (500 ms–10 s). Overall, the findings have been mixed (Kolassa and Miltner, 2006; Rossignol et al., 2007) but suggest that social anxiety is associated with enhanced visual occipito-temporal P1 to faces irrespective of expression (Helfinstein et al., 2008; Kolassa et al., 2007, 2009; Mueller et al., 2009; Mühlberger et al., 2009; Wieser et al., 2010) and right temporo-parietal N170 (Kolassa and Miltner, 2006; Wieser et al., 2010) to angry and happy faces. There is also some evidence in later centro-parietal P3/LPP responses that aversive facial displays are more significant in high social anxiety (Moser et al., 2008; Sewell et al., 2008; but see Wieser et al., 2010) although correspondent enhancements to neutral faces have also been observed as a function of elevated interpersonal apprehension (Mühlberger et al., 2009).[1] In the few studies (Kolassa et al., 2009; Mühlberger et al., 2009) that assessed relative electrocortical responses to expression-types within hedonic valence (pleasant, aversive), socially anxious participants showed commensurate amplitude enhancements across aversive contents (i.e., angry, sad, disgusted, fearful faces).

Concerning neurophysiological underpinnings, hemodynamic imaging studies have revealed that relative to controls socially anxious individuals and patients show exaggerated activation of limbic circuitry, particularly amygdala (Birbaumer et al., 1998; Evans et al., 2008; Phan et al., 2006; Schneider et al., 1999; Stein et al., 2002; Straube et al., 2004, 2005; Veit et al., 2002), in response to emotional facial expressions, again presented for a wide range of durations (i.e., 100 ms–2500 ms). Less frequently an a priori area of interest, concurrent hyper-reactivity has also been observed in the extra-striate visual cortex (Evans et al., 2008; Goldin et al., 2009; Pujol et al., 2009; Straube et al., 2004, 2005). This covariation accords with functional data from unselected (Sabatinelli et al., 2009) as well as specific phobia populations during viewing of fear-relevant pictures (Ahs et al., 2009; Sabatinelli et al., 2005; Schienle et al., 2005) and with structural data from non-human primates revealing such reciprocal cortico-amygdaloid connections (Amaral et al., 2003).

Although the spatial resolution is superior to ERP methods, functional MRI findings lack the temporal specificity necessary for characterizing proposed attention dynamics in social anxiety. Here, we used steady-state visual evoked potentials (ssVEPs) as a continuous measure of visual cortical engagement in processing a visual stimulus (Müller et al., 1998a,b). The ssVEP is an oscillatory response to stimuli modulated in luminance (i.e., flickered), in which the frequency of the electrocortical response recorded from the scalp equals that of the driving stimulus (Müller et al., 1998b; Regan, 1989). Of significant advantage, the oscillatory cortical response is of known frequency and can thus be reliably separated from noise and quantified in the frequency domain (Wang et al., 2007). Generators of the ssVEP have been localized to extended visual cortex (Müller et al., 1997), with strong contributions from V1 and higher order cortices (Di Russo et al., 2007). Importantly, ssVEPs reflect multiple excitations of the visual system with the same stimulus over a brief epoch. Thus, changes in driven neural mass activity can be affected both by initial sensory processing and by subsequent re-entrant, top-down modulation of sensory activity by higher order processes (Keil et al., 2001; Silberstein et al., 1995).

Enhanced sensory responding as indexed with ssVEP amplitude covaries with resource allocation of attention to the driving stimulus. Signal energy increases are reliably observed to visual stimuli as a function of instructed attention (Müller et al., 2003), fear conditioning (Moratti et al., 2006; Moratti and Keil, 2005), and emotional arousal (Keil et al., 2003, 2008), showing high sensitivity to both intrinsic and extrinsic motivations. Viewing pleasant and unpleasant relative to neutral pictures at 10 Hz has consistently shown amplitude enhancements in occipito-parietal recording sites (Keil et al., 2003; Moratti et al., 2004). The affect-modulation of the ssVEP has been proposed to reflect sensory gain enhancement for motivationally significant processing via re-entrant modulatory activity (Keil et al., 2009) from connections such as the parieto-frontal cortex and amygdaloid complex (Baizer et al., 1993; Iwai and Yukie, 1987). As noted, the fMRI findings on social anxiety suggest that pervasive interpersonal apprehension may be characterized by a similar tuning of the sensory gain to emotional facial expressions.

Accounting for time course information, ssVEPs show a near sinusoidal waveform mirroring the stimulus frequency, often accompanied by higher harmonics (Riemslag et al., 1985). Because of their known frequency, ssVEPs can be analyzed not only in the frequency domain (Regan, 1989) but also in the time-frequency domain (Müller et al., 2008). These latter analyses allow researchers to follow the stimulus-evoked contour of the ssVEP at the frequency of interest and thus obtain a continuous measure of visual cortical facilitation related to the eliciting stimulus at near-optimum time resolution. For instance Müller et al. (1998b) found that the time-varying amplitude of the ssVEP during shifts of spatial attention corresponded with near-simultaneous behavioral performance. The ssVEP is especially suited to detecting fluctuations in selective attention over extended time periods, as the recorded signal remains stationary in its spatial distribution. Unlike transient event-related potentials that consist of characteristic spatio-temporal electrocortical dynamics moving over the scalp, ssVEPs represent a stable visual cortical signal, with stable topography, sensitive to temporal changes in visual processing (Hillyard et al., 1997). Essentially ssVEP amplitude provides a productive index of time-varying engagement of neural masses in sensory cortex to a continuously presented stimulus (Regan and Spekreijse, 1977) and hence, informs on the procession of stimulus salience and of top-down regulation of attention.

In the present study, we were interested in the visual cortical dynamics during prolonged (i.e., multiple seconds) exposure to face stimuli varying in emotional expression, for which ssVEP is a judicious dependent variable. Naturalistic facial expressions were presented at 17.5 Hz for 3500 ms to individuals varying in generalized social anxiety and the oscillatory cortical response was recorded with a high-density electrode array (129 sensors). Neutral, happy, fearful, and angry expressions were included as all four conditions have rarely been assessed simultaneously (Mühlberger et al., 2009), thereby precluding conclusions regarding the specificity of enhanced attention in social anxiety. Electrocortical responses were analyzed using the minimum norm estimate (MNE), a distributed source projection algorithm (see Methods). Although not providing precise neuro-anatomical localization, the MNE as implemented here allows one to infer the gross location of the origin of the surface-recorded signal. In addition, generators that are tangential with respect to the scalp tend to be represented as one active area in the MNE, as opposed to two areas, which is the case with voltage or Laplacian maps (Hauk et al., 2002). This is particularly important in situations where sources are located in lower-tier visual cortex, often oriented tangentially to the scalp. Continuous MNE was in turn submitted to time-frequency-

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[1] The observed attentional biases in social anxiety differ when participants anticipate giving a speech following the experimental procedure. High relative to low socially anxious individuals respond faster to probes proceeding household objects than emotional faces (Chen et al., 2002), show faster eye movements but reduced fixation time to emotional than neutral faces (Garner et al., 2006), and demonstrate larger N1 and associated component responses to angry than neutral faces (Wieser et al., 2010).

domain transformation, enabling analysis of changes on the level of modeled sources rather than on the level of voltage maps. The resulting time-varying ssVEP amplitude was averaged into three epochs corresponding to two early windows (100–500 ms, 500–1000 ms) for assessing the possibility of group differences in initial vigilance and a later window to assess sustained processing of the stimulus (1500–3500 ms). These early segments were selected on the basis of preceding work with ssVEP during selective attention tasks, suggesting that the early ramp and the early plateau of the ssVEP (100–500 and 500–1000 ms post-stimulus) may be differentially sensitive to task instructions (Müller and Hillyard, 2000) or stimulus properties (Keil et al., 2006). Thus, with the three segments chosen, we intended to cover aspects of early and late sustained processing, compromising between high time resolution (small time windows) and signal-to-noise (long time windows), where appropriate.

As briefly reviewed, the accumulating literature on attentional biases to facial expressions in social anxiety results from the implementation of a wide range of recording methodologies and stimulus types (naturalistic, schematic, computer-generated) presented for highly variable time intervals (100 ms–10 s). Taken together, the findings remain tentative but generally implicate a hypersensitivity to emotional (particularly angry) expressions evident at multiple time windows. Thus, in the current study high social anxiety was expected to be characterized by electrocortical hyper-reactivity primarily in occipito-parietal regions to emotional (most pronounced to angry) expressions that would be sustained throughout the 3500 ms viewing epoch. An alternative hypothesis, although not strongly supported by empirical data, is also considered here based on patient reports of interpersonal behavior (Trower and Gilbert, 1989) and prominent cognitive-behavioral models of social anxiety (Clark and Wells, 1995; Roth and Heimberg, 2001; Schultz and Heimberg, 2008). That is a pattern also consistent with the vigilance-avoidance hypothesis (Mogg et al., 1997) in which high social anxiety is associated with an amplified cortical response to threatening faces early in the viewing epoch followed by a reduction, reflecting initial hypersensitivity followed by covert disengagement.

Methods

Participants

Thirty-seven (62% female; 76% Caucasian) students from University of Florida undergraduate psychology courses participated for course credit (mean age = 19.65; SD = 1.69). All participants reported corrected to normal vision and a negative personal and family history of seizure disorder. Participants were recruited based on responses to the self-report form of the Liebowitz Social Anxiety Scale (LSAS-SR; Fresco et al., 2001) collected during an online screening procedure. The LSAS-SR is a 24-item scale that indexes the extent of experienced anxiety (0 = none; 3 = severe) and frequency of avoidance (0 = never; 3 = usually) of 24 social interaction and performance situations during the preceding week. The LSAS total, a composite score of social anxiety and avoidance shown to correlate highly with interview-based measures of social anxiety severity (Heimberg et al., 1999) was utilized for screening 2104 individuals (M = 38.92; SD = 21.03; MD = 36). To help ensure the participation of individuals high and low in social anxiety, those endorsing LSAS-SR total scores in the upper and lower tertiles were invited to participate.

The 37 participants who attended the laboratory session were re-administered the LSAS-SR (M = 49; SD = 22.37; MD = 50). Participants endorsing below 40 (n = 14) were identified as "low socially anxious", and those above 60 (n = 14) as "high socially anxious". The gender ratios were equivalent in the high (50% male) and low (42.9% male) symptom groups, X^2 (1) = 0.14, ns. Dichotomous groups were distinguished to enhance generalizability to clinical samples (Borkovec and Rachman, 1979) and, as shown in Table 1, the resulting

Table 1
Questionnaire subscale scores (means and standard deviations) for high and low social anxiety groups.

Measure/subscale	Low social anxiety (N = 14)	High social anxiety (N = 14)	Group effect
Liebowitz Social Anxiety Scale (LSAS-SR)			
Total social fear and avoidance	25.07 (9.06)	72.50 (8.64)	$F(1,26) = 201.04$, $p < 0.001$
Interaction fear	5.71 (3.07)	18.79 (3.29)	$F(1,26) = 118.14$, $p < 0.001$
Interaction avoidance	5.93 (4.07)	17.93 (3.29)	$F(1,26) = 73.65$, $p < 0.001$
Performance fear	7.57 (2.24)	19.21 (3.58)	$F(1,26) = 106.44$, $p < 0.001$
Performance avoidance	5.93 (2.21)	17.93 (4.20)	$F(1,26) = 71.28$, $p < 0.001$
Mood and Anxiety Symptom Questionnaire (MASQ)			
Non-specific distress	30.43 (10.71)	34.71 (8.56)	$F(1,26) = 1.37$, ns
Non-specific anxiety	18.29 (5.59)	21.0 (5.35)	$F(1,26) = 1.72$, ns
Non-specific depression	19.64 (7.23)	25.14 (8.64)	$F(1,26) = 3.34$, ns
Anhedonia	52.29 (7.93)	55.36 (10.14)	$F(1,26) = 0.80$, ns
Anxious arousal	25.57 (8.87)	23.64 (5.39)	$F(1,26) = 0.49$, ns

Note. Liebowitz Social Anxiety Scale Self-report Version (LSAS-SR; Fresco et al., 2001); Mood and Anxiety Symptom Questionnaire (MASQ; Watson and Clark, 1991; Watson et al., 1995).

mean total (M = 72.5) and subscale scores for the high socially anxious group are similar to those observed for treatment-seeking individuals diagnosed with generalized social anxiety disorder (LSAS-SR: Baker et al., 2002; Fresco et al., 2001; Rytwinski et al., 2009; LSAS-I: Cox et al., 1998; Heimberg and Holaway, 2007). Furthermore, the normative subscale scores for the Mood and Anxiety Symptom Questionnaire (MASQ; Watson et al., 1995) for the same participants indicate that rather than reflecting broad dysphoria, the elevated distress in this group is specific to social anxiety (Table 1).

Stimuli

Ninety-six pictures were selected from the Karolinska Directed Emotional Faces (KDEF; Lundqvist et al. (1998); http://www.facialstimuli.com/) of 24 actors gazing directly at the viewer (12 female, 12 male actors) posing 4 different expressions (neutral, happy, fearful, and angry). Stimuli were pre-processed by means of the MATLAB image processing toolbox to have equal overall lightness and color composition.

Pilot study: normative ratings of facial expressions

For comparison with prior face-processing studies (e.g., Kolassa and Miltner, 2006) as well as ssVEP investigations of emotional scenes (e.g., Keil et al., 2003), an online pilot study was conducted to gather normative affective ratings of the 96 stimuli selected for the laboratory session. This study allowed us to collect complementary evidence as to whether or not the face stimuli were effective in conveying the intended expression and, in turn, elicited a reliable affective response in viewers. The rating study also aimed to inform the present study regarding potential stimulus differences in emotional intensity, known to affect the ssVEP (Moratti et al., 2004). For course credit 140 students (mean age = 19.65; SD = 0.99; 67.9% female) from undergraduate psychology courses provided informed consent and then viewed and rated pseudorandom presentations of each facial expression with the Self-Assessment Manikin (SAM; Bradley and Lang, 1994) to assess three dimensions: experienced pleasure, emotional arousal, and dominance. See Table 2 for means and standard deviations. Repeated measures ANOVAs were performed separately on these dimensions with facial expression as the within-subjects factor. Arousal varied across expressions,

Table 2
Normative pleasure, arousal and dominance ratings ($N = 140$) of KDEF stimuli on Self-Assessment Manikin (SAM) by expression.

Facial expression	Pleasure	Arousal	Dominance
Neutral	4.62 (0.54)	3.61 (1.36)	5.28 (1.85)
Happy	7.12 (0.98)	4.47 (1.76)	5.29 (2.21)
Fearful	3.75 (1.02)	4.93 (1.46)	4.81 (2.16)
Angry	3.41 (1.09)	5.07 (1.49)	5.21 (2.03)

Note. Pleasure rated on SAM (Bradley and Lang, 1994; Lang, 1980): 1 = completely unhappy, 9 = completely happy; Arousal: 1 = completely relaxed, 9 = completely aroused; Dominance 1 = completely dominant, 9 = completely submissive.

$F(3,137) = 52.78$, $p < .001$, $\eta_p^2 = 0.54$, with the most intense ratings for angry, followed by fearful, happy, and lastly neutral. The mean arousal for all expressions reliably differed, contrasts $Fs = 6.92–154.54$, $ps < 0.01$, including the two most arousing conditions, fearful versus angry, $F(1,139) = 6.92$, $p < 0.01$. Expression also influenced hedonic valence, $F(3,137) = 258.92$, $p < 0.001$, $\eta_p^2 = 0.85$, with the most aversion reported for angry, followed by fearful, and the most pleasure for happy expressions. Similar to rated arousal, the mean pleasure for all expressions reliably differed, contrasts $Fs = 48.64–782.44$, $ps < 0.001$. Participants endorsed intermediate dominance ratings across all expressions, $F(3,137) = 1.93$, *ns*, indicating feeling neither in control or dominated.

Laboratory procedure

Upon providing informed consent in the laboratory, participants were seated in a sound-attenuated, dimly lit room and the EEG sensor net was attached. Participants were instructed that a series of pictures would be displayed and that they should view each picture for the duration of presentation, keeping their eyes comfortably focused on the center of the screen.

Controlled by an IBM-compatible computer running MATLAB and functions from the Psychtoolbox suite (Brainard, 1997) faces were presented 116 cm from the participant on a 51-cm monitor with a vertical refresh rate of 70 Hz, subtending a visual angle of 5° horizontally and 6.9° vertically. Pictures were presented in a random order, each presentation flickering at a rate of 17.5 Hz (i.e., 1 cycle = 28.57 ms picture + 28.57 ms of black screen) for 3428 ms (60 cycles) followed by a randomly variable 2–4-s inter-trial interval.

At the completion of the EEG recording participants were administered the LSAS-SR and the MASQ (Watson et al., 1995) and then debriefed.

EEG recording and data collection

Electroencephalogram (EEG) was continuously recorded from 129 electrodes using an Electrical Geodesics (EGI) HydroCel high-density EEG system with NetStation software on a Macintosh computer. The EEG recording was digitized at a rate of 250 Hz, using Cz as a recording reference. As suggested for the EGI high input impedance amplifier by the manufacturer, and supported by empirical studies of signal-to-noise ratios under varying impedance levels (Ferree et al., 2001), electrode impedances were kept below 50 kΩ. This procedure is standard in studies using the EGI dense-array system and has been validated in a plethora of published studies of EEG and event-related potentials (Junghöfer et al., 2000). A subset of electrodes located at the outer canthi and below the right eye was used to determine the horizontal and vertical electrooculogram (EOG). All channels were pre-processed online by means of 0.1 Hz high-pass and 100 Hz low-pass filtering. Epochs were extract from the continuously recorded EEG relative to the onset of each picture, using 300 ms pre- and 4400 ms post-picture onset, data were low-pass filtered at a frequency of 30 Hz (48 dB/octave, 18th order Butterworth filter) and then submitted to the procedure proposed by Junghöfer et al. (2000),

as implemented in the EMEGS software suite provided by Peyk and Junghöfer (www.emegs.org). This procedure used statistical parameters of the data to exclude channels and trials that were contaminated with artifacts. Recording artifacts were first detected using the recording reference (i.e., Cz), and then global artifacts were detected using the average reference, which was used for all analyses. Cz was used for recording only, and the average reference was calculated after artifact rejection and used for all subsequent analyses. The average reference is considered an acceptable solution to the problem of reference-dependent topographies (Junghöfer et al., 1997) and is particularly suitable in multi-electrode studies with sufficient coverage of the volume conductor, i.e., the head (Bertrand et al., 1985). Subsequently, distinct sensors from particular trials were removed based on the distribution of their amplitude, standard deviation, and gradient. Data at eliminated electrodes were replaced with a statistically weighted spherical spline interpolation from the full channel set (Junghöfer et al., 2000). After artifact correction, an average of 72% of trials/condition was retained in the analyses.

Steady-state VEP analyses

Grand mean time-locked averages of the voltages recorded during the angry expressions for all 37 participants are shown in Fig. 1 to demonstrate that the expression conditions evoked reliable and pronounced 17.5 Hz oscillation, clearly time-locked across conditions and separable from noise.

Artifact free epochs of the voltage data were averaged by condition and projected to an estimated source space using the minimum norm estimation (MNE) method proposed by Hauk (2004) and Hauk et al. (2002). Among other advantages, this source projection method reduces the amount of topographical variability between individual participants, because it tends to veridically represent the origin of tangential dipolar electric fields: The ssVEP elicited by rapid flicker has been shown to have deep, mostly calcarine sources, associated with tangential dipolar fields. Deep sources tangential to the scalp surface may result in very different voltage maps, depending on the orientation of the generator structure in a given participant. The MNE reduces this variability dramatically (Hauk et al. 2002) by indicating a spatially smeared maximum near the true signal origin instead of remote positive and negative voltage gradients. This is especially beneficial for studies of interindividual differences.

On a source space consisting of four concentric spheres, dipoles were placed equidistantly to approximate the brain volume. This source space contained 655 source locations (i.e., the model sources). A high number of model sources are needed for the initial calculation of the MNE to capture the scalp-recorded potential at sufficient spatial resolution, to avoid mislocalization (Hauk, 2004). To capture voltage gradients in all possible directions currents were modeled for three spatial orientations orthogonal to each other (1 radial, two tangential
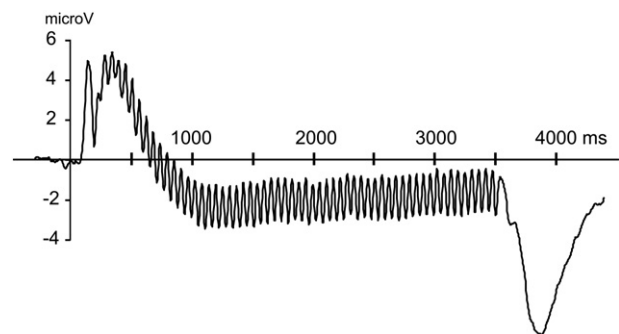

Fig. 1. Grand mean time-locked averages of the voltages over eight occipital sensors recorded during angry expressions for all 37 participants are shown to demonstrate that the expression conditions evoked reliable and pronounced 17.5 Hz oscillation, clearly time-locked across conditions and separable from noise.
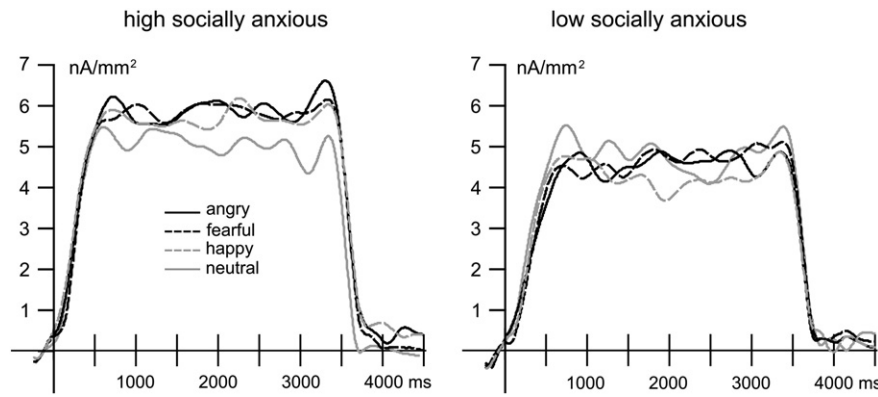
Fig. 2. The time-varying ssVEP amplitude (nA/mm²) averaged over eight occipital sensors for the angry, fearful, happy and neutral facial expression conditions for participants high and low in social anxiety.

relative to the scalp surface) at each source location. The four shells had the radii 0.8, 0.6, 0.4, and 0.2 relative to the electrode radius of 1. For regularization the Tikhonov–Philips approach was used to suppress uncorrelated noise (Hauk, 2004). From the source space, the shell at 0.6 of the radius was selected as a compromise between depth sensitivity and spatial resolution (Hauk et al., 2002). After calculation of the solutions, the 655 model sources were reduced by selecting the 129 sources located closest to the electrode positions, for mapping purposes and statistical analyses. This procedure leaves the originally estimated source distribution intact (Hauk et al., 2002). At each of the resulting 129 source locations the time-varying amplitude at the stimulation frequency of 17.5 Hz was extracted by means of complex demodulation (Regan, 1989), separately for the three orientations of the MNE. The averaged condition data were multiplied with a sine and cosine function at the stimulation frequency. The resulting time series were then digitally low-pass filtered using a third-order Butterworth filter, set at a cutoff of 1.5 Hz. This led to sensitivity of the resulting waveforms to amplitude changes between 16 Hz and 19 Hz, with a center frequency of 17.5 Hz. The time resolution of the resulting metric was 120 ms (full width at half maximum). Next, the three dipole orientations at each source location were combined by means of the modulus (Euclidean distance) for a measure of current density (nanoamperes/mm²). Subsequently, the time course of the ssVEP was baseline corrected for each channel by subtracting the mean time-varying ssVEP current density in a segment between −240 and −120 ms, prior to stimulus onset. This baseline segment ended well before stimulus onset, to avoid contamination of the baseline estimate with post-stimulus activity due to the temporal smearing of the complex demodulation.

For each participant and condition the ssVEP source strength was averaged into three epochs corresponding to two early windows (100–500 ms and 500–1000 ms) for assessing the possibility of group differences in initial vigilance and a later window to assess more sustained processing (1500–3500 ms, see the preceding text for the rationale underlying these temporal segments). Repeated measures ANOVA was performed with group status (high versus low social anxiety) as the between-subjects factor and facial expression and time as the within-subjects factor. ssVEPs have been shown to strongly co-vary with rated emotional arousal (Keil et al., 2003, 2009), thus contents were entered according to the linear increase in arousal for KDEF stimuli demonstrated in the normative sample (i.e., neutral, happy, fearful, and angry) as well as previous samples (Mühlberger et al., 2009). To provide a quantitative means of assessing significant interactions of expression condition and group, within-group repeated measures analyses and simple planned contrasts of ssVEPS to emotional (happy, fearful, and angry) relative to neutral displays were utilized. Effects of time were similarly analyzed. Wilks' lambda addressed sphericity issues (Vasey and Thayer, 1987).

As observed in previous steady-state examinations (e.g., Müller et al., 2008) dipole source strength was most pronounced over the occipital pole, near electrode Oz. Thus, mean time-varying amplitudes in the three time windows (100–500 ms, 500–1000 ms, and 1500–3500 ms) were averaged across an occipital electrode cluster comprising Oz as well as 7 neighboring sensors (70 73 74 75 81 82 83 88) for each participant.

Results

High versus low social anxiety: ssVEP dipole source strength to facial expressions

In Fig. 2 the time-varying ssVEP amplitude for the four expression conditions is shown for participants high and low in social anxiety defined according to the total symptom score of the LSAS-SR.

Repeated measures ANOVA with group status (high versus low social anxiety) as the between-subjects factor and facial expression (neutral, happy, fearful, and angry) and time (100–500 ms, 500–1000 ms, and 1500–3500 ms) as the within-subjects factors revealed that mean ssVEP amplitudes varied over the presentation epoch, $F(2,25) = 18.15$, $p < 0.001$, $\eta_p^2 = 0.59$, in a pattern similar across groups, Time × Group, $F(2,25) = 0.13$, ns, and expression, Time × Expression, $F(6,21) = 2.56$, $p = 0.05$, $\eta_p^2 = 0.42$; Time × Expression × Group, $F(6,21) = 1.13$, ns. A significant interaction emerged between high and low socially anxious participants in relative sensitivities to expressions, Group × Expression, $F(3,24) = 5.08$, $p < 0.01$, $\eta_p^2 = 0.39$, whereas ssVEP amplitudes did not differ by expression when considered irrespective of group status, $F(3,24) = 0.37$, ns, and no overall group difference emerged in the mean amplitude of evoked responses, $F(1,26) = 0.51$, ns.[2]

Follow-up tests of the main effect of time reflected that as shown in Fig. 2 the mean ssVEP amplitude reliably increased from the first (100–500 ms) to second stimulation epoch (500–1000), $F(1,27) = 38.67$, $p < 0.001$, $\eta_p^2 = 0.59$, and then maintained this level for the duration of the presentation, $F(1,27) = 0.34$, ns.[3]

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[2] In follow-up analyses gender exerted neither a main effect nor an interaction on ssVEP amplitude to emotional and neutral facial expressions: Gender, $F(1,24) = 0.02$, ns, Gender × Time, $F(2,23) = 2.44$, ns, Gender × Expression, $F(3,22) = 1.78$, ns, Gender × Time × Expression, $F(6,19) = 0.81$, ns, Gender × Expression × Group, $F(3,22) = 1.20$, ns, Gender × Expression × Time × Group, $F(6,19) = 0.40$, ns.

[3] Guided by preceding work with selective attention tasks ssVEP amplitude was averaged into three epochs corresponding to two early (100–500 ms and 500–1000 ms) and one later windows (1500–3500 ms). For completeness, analyses were also performed on the ramp (100–500 ms) and two equal-length subsequent windows (500–2000 and 2000–3500 ms). The results underscored the pattern differences in the symptom groups: Group × Expression, $F(3,24) = 5.83$, $p < 0.01$, $\eta_p^2 = 0.42$; Time, $F(2,25) = 15.61$, $p < 0.001$, $\eta_p^2 = 0.56$, Expression, $F(3,24) = 0.43$, ns, Group, $F(1,26) = 0.56$, ns, Time × Group, $F(2,25) = 0.05$, ns, Time × Expression, $F(6,21) = 2.19$, ns, Time × Expression × Group, $F(6,21) = 0.83$, ns.
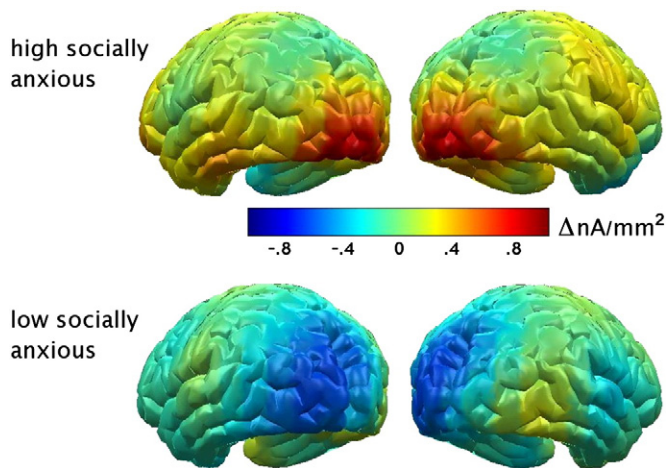
Fig. 3. The difference in the topographical distribution of the ssVEP source strength (nA/mm²) for emotional relative to neutral facial expressions (averaged across epochs) for participants high and low in social anxiety.

Fig. 4. Association between LSAS-SR total score on the y-axis, and increase in source strength amplitude (nA/mm²) during emotional relative to neutral facial expressions on the x-axis for all 37 participants.

To explore the omnibus group by expression interaction, repeated measures analyses were performed separately for the groups (averaging across epochs). While low socially anxious individuals demonstrated no modulation of the ssVEP amplitude as a function of expression (Fig. 2), $F(3,11) = 2.16$, ns, high socially anxious participants tended to show greater sensitivity to emotional displays, $F(3,11) = 3.55$, $p = 0.05$, $\eta_p^2 = 0.49$: happy, fearful, and angry expressions each elicited larger mean amplitude responses than neutral presentations, $Fs = 5.03–6.91$, $ps < 0.05$. Follow-up univariate ANOVAs on the difference scores demonstrated that this augmentation in the high socially anxious group for happy, $F(1,26) = 7.16$, $p < 0.05$, $\eta_p^2 = 0.22$, fearful, $F(1,26) = 8.33$, $p < 0.01$, $\eta_p^2 = 0.24$, and angry, $F(1,26) = 12.86$, $p < 0.01$, $\eta_p^2 = 0.33$, relative to neutral expressions, all reliably exceeded the respective source strength differences in the low socially anxious group. Notably, as shown in Fig. 2 the increase in amplitude relative to neutral for the high socially anxious group was similar across happy, fearful, and angry expressions, indicating a broad sensitivity to emotional facial displays.

The difference in the topographical distribution of the ssVEP source strength for emotional relative to neutral expressions (averaged across epochs) by symptom group is illustrated in Fig. 3. As high socially anxious participants showed enhanced sensitivity to emotional faces regardless of specific expression, the mean amplitude increases during happy, fearful, and angry expressions were also averaged for this analysis. Notably, the increased amplitude to emotional versus neutral contents in the high symptom group was distinctly circumscribed to the visual cortex.

Dimensional social anxiety, broad dysphoria, and sensitivity to emotional expressions

To extend the findings for the dichotomous comparison of 14 high versus 14 low socially anxious participants, the LSAS-SR total severity score was correlated with the mean amplitude difference during emotional relative to neutral expressions (averaged across epochs) for the total sample of 37 participants. As illustrated in Fig. 4, there was a significant bivariate correlation between LSAS-SR total score and increase in amplitude during emotional relative to neutral expressions, Spearman's rho: $r_s(37) = 0.62$, $p < 0.001$, such that as social anxiety symptom severity increased, the difference in mean ssVEP amplitude during emotional relative to neutral expressions increased. To assess this association in relation to broad negative affectivity, hierarchical multiple linear regression was employed with MASQ subscale scores (non-specific distress, non-specific anxiety, non-specific depression, anhedonia, anxious arousal) entered as the
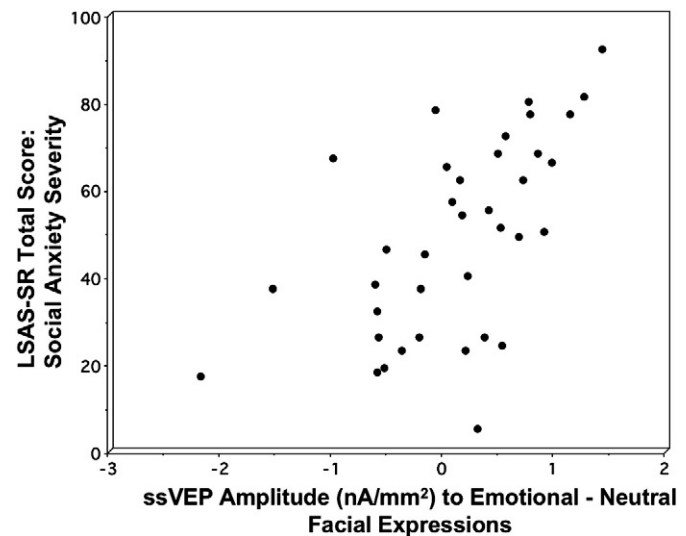
first block and LSAS-SR total score as the second block.[4] MASQ subscale scores did not predict ssVEP amplitude during emotional relative to neutral expressions, $\Delta R^2 = .17$, $\Delta F(5,31) = 1.29$, ns, whereas even after partialing out variance attributable to broad anxious and depressive symptomatology, social anxiety accounted for 27% of the total variance in amplitude difference during emotional versus neutral expressions, $\Delta F(1,30) = 14.37$, $p < 0.001$. Specificity of the positive association between social anxiety and expression differentiation was underscored in the standardized coefficients for the simultaneous model: social anxiety, $\beta = 0.62$, $p < 0.01$; non-specific distress, $\beta = -0.19$, ns, non-specific anxiety, $\beta = 0.15$, ns, non-specific depression, $\beta = -0.06$, ns, anhedonia, $\beta = 0.09$, ns, anxious arousal, $\beta = -0.28$, ns.

Discussion

In the current study continuous steady-state visual evoked potentials to naturalistic emotional and neutral facial expressions were assessed in individuals varying in generalized social anxiety. Evoked responses were recorded with a high-density EEG montage and distributed source modeling (minimum norm estimate) was used to infer electric source distribution and strength, and thus to elucidate the neural mechanisms underlying putative perceptual processing differences in social anxiety. Similar to a subset of preceding studies and consistent with predictions based on the clinical nosology, high social anxiety was characterized by exaggerated visual responses to angry relative to neutral facial expressions. However, enhanced neural mass activity in visual cortex was not limited to stimuli connoting interpersonal challenge, disapproval and/or rejection. Instead, commensurate occipitocortical facilitation was observed in response to other aversive (fearful) as well as appetitive (happy) expressions, implicating a broad visual sensitivity to emotional facial displays in social anxiety. In contrast, individuals endorsing low interpersonal apprehension demonstrated no modulation of the ssVEP amplitude as a function of expression—all facial displays were seemingly innocuous. Furthermore, the signature of enhanced perceptual salience of emotional displays at higher symptom levels was demonstrated in both categorical and dimensional analyses, the latter suggesting a strong linear relationship.

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[4] Tolerance (0.3–0.8) values for each predictor indicated non-redundancy of the symptom measures in predicting ssVEP amplitude.

Although heightened sensitivity specific to angry expressions would seem most consistent with the nosology of social anxiety, vigilance to other expressions has frequently been revealed in both ERP (Kolassa et al., 2007, 2009; Wieser et al., 2010) and hemodynamic imaging (Amir et al., 2005; Birbaumer et al., 1998; Phan et al., 2006; Stein et al., 2002) studies—even to happy faces (Yoon et al., 2007; Straube et al., 2005) and aversive non-social scenes (Shah et al., 2009). Much of the evidence for exaggerated reactivity to "harsh" facial expressions has been demonstrated as the mean response to heterogeneous aversive displays (angry, fearful, and disgusted) (e.g., Moser et al., 2008; Phan et al., 2006; Stein et al., 2002). In post hoc tests of the BOLD response to individual aversive contents, Phan and colleagues revealed that the overall effect was attributable to reliable, similar magnitude amygdala activity to angry, fearful and disgusted faces.

Whereas early and later event-related components have shown sensitivity to emotional versus neutral facial expressions in unselected samples (Eimer and Holmes, 2007; Schupp et al., 2004), the absence here of an expression differentiation among individuals low in social anxiety is consistent with a subset of prior studies that specifically isolated a minimal symptom group. For example, no differences in early (Mueller et al., 2009) and later event-related positivities (Kolassa et al., 2007) have been observed. These data, notably, are not directly comparable to the present findings as ERPs reflect spatio-temporal transient responses throughout the entire cortex, whereas the ssVEP indexes fluctuations in sustained sensory processing. Nonetheless, in a recent study ssVEP amplitudes to emotional and neutral expressions also did not differ (Wieser et al., in press) among participants who endorsed minimal interpersonal apprehension. As a further complement, Bar-Haim et al. (2007) concluded on the basis of a meta-analysis that attention biases towards threat stimuli are most reliably seen in high anxious and patient groups, but are less reliable in low anxious samples. Additionally, the affective ratings collected for this as well as other investigations (Goeleven et al., 2008) suggest that in an unselected sample, naturalistic facial expressions evoke at most, moderate levels of subjective arousal coupled with moderate unpleasantness or pleasantness—ratings much less extreme than typically observed for emotional scenes that evoke robust physiological differentiation irrespective of individual differences (Bradley et al., 2001; Keil et al., 2003).

The time-varying ssVEP amplitude is a continuous measure of sensory activation at the stimulation frequency. Thus, it is sensitive to potential differences between groups or experimental conditions in terms of temporal dynamics (Müller et al. 2008). In the present study, we did not find evidence of a dynamic change during the viewing epoch, but a sustained enhancement of neural mass activity in visual cortex for emotional expression, specific to participants with high social anxiety. The minimum norm estimate was utilized here to enhance the resolution of steady-state responses without constraining the inferred electric activity to point sources or single dipoles (Hämäläinen and Ilmoniemi, 1984). The resulting topographical distribution of the source strength to the facial displays suggests that the ssVEP signal was generated predominantly in the medial occipital cortex and the bilateral occipital poles in both groups, throughout the 3500 ms viewing epoch. Furthermore, the increased amplitude to emotional relative to neutral pictures in the high social anxiety group was strictly localized to the same regions. Whereas in the previous studies affective modulation of the ssVEP more broadly extended from striate and extrastriate to higher order visual cortical areas such as occipito-temporal, parietal, and fronto-parietal regions (Keil et al., 2003; Moratti et al., 2004) no such concordance characterized the emotional sensitivity demonstrated by the high symptom group. The focused occipital activation in the current study is not wholly unexpected as the stimulation frequency (17.5 Hz) appreciably exceeded that of the aforementioned investigations, and dipole sensitivity to the driving frequency (Müller et al., 1997) has been demonstrated in selective attention paradigms with higher

frequencies ($\geq$ 20 Hz) associated with very narrow and lower level occipital sources (Müller et al., 1998a). Presumably, the prominent affective modulation of the primary visual response elicited here in the high socially anxious is the result of re-entrant signals from anterior cortical areas, ultimately originating in higher visual, deep, and/or subcortical structures (Keil et al., 2009), that tune visual cortical neurons, altering thresholds and/or enhancing gain in the networks representing interpersonal evaluative cues.

The possible reorganization of the sensory visual cortex correspondent to alterations in motivational thresholds associated with excessive social apprehension is supported by animal and human work revealing that the functional neuroarchitecture of the adult visual cortex is subject to changes related to behavioral contingencies (Karmarkar and Dan, 2006; Li et al., 2004) and re-entrant modulation from higher visual areas including temporal cortex and deep structures such as the amygdala (Damasio, 1998; Leppänen and Nelson, 2009; Sabatinelli et al., 2005, 2009)—areas consistently shown during functional neuroimaging to be hyper-reactive to facial stimuli in social phobia patients (Birbaumer et al., 1998; Evans et al., 2008; Phan et al., 2006; Schneider et al., 1999; Stein et al., 2002; Straube et al., 2004; Veit et al., 2002). Although speculative, the heightened attention to emotional faces may be the result of visual system plasticity secondary to chronic expectations of interpersonal failure typical of social anxiety (Andrews et al., 1994; Foa et al., 1996; Poulton and Andrews, 1996; Rapee and Heimberg, 1997). Complementing the broad attentional enhancement to aversive and pleasant facial displays observed here, recent findings from other laboratories indicate that social anxiety is marked by fear not only of negative (Clark and Wells, 1995; Rapee and Heimberg, 1997) but also of positive (Fergus et al., 2009; Weeks et al., 2008a,b) evaluation. Others have postulated that either pleasant or unpleasant relative to neutral interactions increase perceived interpersonal performance demands in social anxiety, and hence, the perceived inevitability of failure (Fergus et al., 2009; Weeks et al., 2008a,b).

Guided by compelling accounts of cognitive processing stages in clinical social anxiety (Trower and Gilbert, 1989), the literature is replete with speculation concerning the temporal dynamics of visual processing biases in the disorder, most of which promotes the vigilance-avoidance hypothesis—that in pathological anxiety perception of threat-relevant stimuli is characterized by initial hypervigilance and consequent defensive avoidance (Mogg et al., 1997). To date, however, as briefly reviewed, the dot-probe, oculomotor, ERP, and fMRI data with socially anxious individuals and patients lack the temporal resolution for addressing the proposed unfolding of attentional engagement and disengagement to facial expressions. In the current study, employing a continuous measure of perceptual processing capable of quantifying covert attention shifts revealed broad, sustained sensitivity to emotional expressions evident over the entire 3500 ms stimulation epoch in social anxiety. Future studies are warranted to disentangle effects specific to the onset of the stimulus train from those secondary to shifting the facial expression amidst an ongoing train (i.e., flickering neutral to flickering angry face), but these preliminary results showed facilitated attention among socially anxious individuals to emotional expressions as early as the first 500 ms with no evidence of subsequent perceptual avoidance.

Although the severity of generalized social anxiety reported in the current high symptom sample was commensurate to patients in prior clinical investigations, the implications of these results for explicating disorder-level dysfunction in social anxiety is necessarily limited by the use of an analogue sample. For example, the limited comorbid symptomatology and the mean age of 20.6 years in the high socially anxious group caution that the visual sensitivities observed here may be indicative only of the early stages of social anxiety, prior to the development of the broad negative affectivity characteristic of older treatment-seeking samples (Brown et al., 2001; Kessler et al., 1999). Future investigations are warranted that consider the developmental

course of social anxiety and the role of co-occurring conditions in these affective dispositions. At the same time, the specific nature of the social fearfulness in the current sample was advantageous. Recent evidence has shown that concurrent depression may abolish attentional biases (Musa et al., 2003) and reduce defensive responding (McTeague et al., 2009) in social anxiety, and as such symptom profiles indicative of limited comorbidity are necessary for investigating attentional processes putatively unique to the disorder.

In summary, as assessed here, during passive viewing generalized social anxiety was associated with sustained and amplified visual processing of affective social cues, suggesting that enduring, extreme fear may tune visual sensory gains parallel to mechanisms of phasic selective attention (Hillyard and Anllo-Vento, 1998). Future studies are warranted to determine whether this enhanced sensitivity to emotional faces is characteristic not only of generalized social anxiety, but also of circumscribed performance phobia and/or other anxiety disorders. Additionally, it will be essential to assess whether other indices of motivated attention (Bradley, 2009; Lang and Bradley, 2010) such as skin conductance, heart rate, facial electromyography, event-related potentials, subjective judgments, and performance converge with the findings for ssVEP amplitudes to facial expressions. Furthermore, with the growing implementation of attentional modification interventions for social anxiety utilizing facial stimuli (e.g., Amir et al., 2008, 2009; Schmidt et al., 2009), the continuous measure of perceptual processing provided by the steady-state procedure may help to elucidate covert, temporal dynamics underlying the reported symptom reductions.

Conflict of interest

All authors report no biomedical financial interests or potential conflicts of interest.

Acknowledgments

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