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Reduction in lower-alpha power during Ganzfeld flicker stimulation is associated with the production of images and trait positive schizotypy

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Abstract

Light-flicker Ganzfeld (LFG) induces a lower to upper-alpha frequency shift. However, it is unclear how this neurophysiological response might relate to LFG-induced pseudo-hallucinatory phenomena. It is also unknown whether emotional states (e.g., fear) or traits associated with risk for psychosis (e.g., proneness to perceptual anomalies, ability to produce vivid mental imagery) affect such neurophysiological and/or perceptual responses to LFG. The present study investigated alpha sub-bands during LFG across several flicker frequencies, in relation to individual differences in propensity for Ganzfeld-induced imagery (GI), positive schizotypy and trait mental imagery, and in relation to manipulations of affective state. Given previously reported sex differences in risk for psychosis and response to Ganzfeld, the effect of sex on GI was also studied. Forty-six healthy adults (16 men) completed psychometric measures of trait mental imagery and positive schizotypy before undergoing three LFG (20 minutes each) conditions. In each condition, participants wore white-out goggles and listened to either mood-inducing soundscapes (fear, serenity) or pink noise (control) through headphones. Greatest propensity for GI arose between 12-16 Hz flicker, with a peak at 16 Hz flicker. Occipital lower-alpha was reduced for lower flicker frequencies (12-16 Hz) and was inversely associated with GI. Upper-alpha power was not significantly related to GI or to other measures. Fear-induction was associated with reduction in alpha power, but did not significantly affect GI. Men reported more GI than women. Findings support a role for cortical destabilisation, as reflected in reduced lower-alpha, in perceptual anomalies; and, by extension, LFG as an experimental model of liability to psychosis.

1. Introduction

The idea of a dimensional continuum of frequency and severity of psychotic-like experiences has accrued considerable support [1-5], with concepts such as positive schizotypy or psychosis proneness referring to normal variation in the propensity for experiencing hallucinations and other perceptual anomalies [6, 7]. Indeed, between 1.5 and 39% of the general population experience hallucinatory phenomena and other psychotic-like experiences [4, 8-10]. Investigation of brain structure and function in relation to positive schizotypy [11] and hallucinations in clinical populations [12], has increased understanding of biological mechanisms underpinning anomalous perceptions. Brain activity has also been investigated during Ganzfeld conditions, known to induce pseudo-hallucinatory experiences in the general population [13-16]. However, the relationship between neurophysiological changes associated with Ganzfeld imagery and individual differences in positive schizotypy has not been investigated. Studies in Ganzfeld imagery therefore currently have limited scope for informing neurocognitive models of psychosis proneness *per se*.

One theory proposes that hallucinations and perceptual anomalies develop from an imbalance between 'bottom-up' and 'top-down' influences over perception [17]. From a bottom-up perspective, the presence and severity of hallucinations is associated with damage to sensory organs (e.g., Charles Bonnet syndrome [18]), and/or neural structures involved in early sensory processing (e.g., thalamus [19], primary sensory cortices [12, 20, 21], and also parietal cortex [22]). In the absence of adequate bottom-up stimulation, top-down mechanisms (e.g., internal dialogue, mental imagery, expectations, or prior world-knowledge), can compensate by projecting information back from higher to lower levels of processing, biasing lower-level mechanisms' treatment of incoming signals and noise [23]. This unopposed top-down bias can result in internal experiences' attaining greater salience and therefore influence over the final percept. According to such models, an undue reliance on information originating from top-down sources at the perceptual level may lead to aberrant perceptions, such as hallucinations. In early psychosis and in healthy people prone to psychosis, such a bias manifests as a shift in visual information processing that favours prior knowledge over incoming sensory inputs [24]. Thus, vivid mental imagery is reported in

relation to frank psychotic disorders, and also in unaffected, first-degree relatives of patients with psychosis [25, 26], and as a correlate of schizotypy [27]. One theory proposes that psychosis-prone individuals are less able to distinguish real perception from endogenously generated mental imagery, particularly when imagery is vivid [28]. However, not all studies support this view [29-32]. For example, although patients with schizophrenia report greater vividness of mental imagery compared to healthy controls, this vividness is unrelated to individual psychopathology (e.g., frequency of hallucinations) [33]. Thus, the relationship between hallucinatory experiences and mental imagery remains unclear.

In line with the above ideas, pseudo-hallucinations have been experimentally induced during sensory deprivation [34, 35], and the perceptual degradation of stimuli (e.g., the white Christmas effect), especially in those high in fantasy proneness [36]. One such class of perceptual manipulations, Ganzfeld conditions, involves a homogeneous visual field which can be created using light-diffusing goggles. Under Ganzfeld conditions, some individuals report imagery that is subjectively similar to, but neurophysiologically distinct from, hypnagogic hallucinations [37]. Such Ganzfeld-induced Imagery (GI) ranges from simple Purkinje-type images to more complex forms [13, 16, 37]. Random light-flicker used to produce a less structured sensory stimulation also produces GI [14, 15], particularly with flicker frequencies below 40 Hz, but more so between 6-26 Hz [14, 38]. Whilst some inconsistencies exist in specific frequencies of peak imagery, Becker and Elliot (2006) found that the median frequency for peak reports of a range of different simple forms and colours was 16 Hz [38]. Compared to static Ganzfeld, flicker Ganzfeld more readily produces elementary visual patterns, although more complex images have also been reported.

Static homogeneous sensory conditions and light flicker affect electroencephalographic (EEG) activity in the alpha range (8-12 Hz), suggesting a decoupling of thalamo-cortical networks [13-15, 37]. Statistically and functionally distinct alpha frequency bands (lower 8-10 Hz, upper 10-12 Hz) have been differentiated [39, 40]. A shift from lower- to upper-alpha frequencies has been reported under Ganzfeld conditions [13, 15], and has been hypothesised to underpin image formation [13]. However, there is little direct evidence on whether changes in individual neurophysiological function relate to individual differences in the propensity to

experience GI. One small case study (n=3) found that the appearance of hallucinatory colours due to light-flicker Ganzfeld was preceded by a decrease in lower-alpha (8-10 Hz) power [41], a finding consistent with known decreases in alpha power associated with aberrant percept formation in the context of the McGurk illusion [42]. Additionally, reduced alpha activity (power and coherence) has been shown in schizophrenia both at rest [43], and during sensory and cognitive tasks [44, 45], and is associated with psychotic symptoms [46, 47]. Given that alpha is proposed to reflect active inhibition of cortical function, such findings would be in line with a dysregulation of cortical activity which in the context of limited sensory input could result in hallucinatory phenomena. However, LFG would also be expected to elicit entrainment or the steady-state response (SSR) [48], a phenomenon whereby neurons synchronise their firing to the frequency of incoming stimulation. This is apparent when neurons in visual cortex respond to flickering light, especially in response to 10 Hz flicker, at which frequency the SSR is superimposed on endogenous upper-alpha activity [49, 50].

Emotional state might also be expected to affect GI, as the role of top-down emotional feedback in the formation of visual hallucinations and perceptual anomalies has been linked to amygdala-visual cortex hyperconnectivity [51]. The propensity for hallucinations increases with negative affect, poor reality discrimination, and intrusive cognitions [52-56]. For example, intense emotion disrupts reality monitoring in non-psychotic children experiencing hallucinations [55], and could underpin the common hallucination of a deceased loved one during bereavement (e.g., [54, 57]). However, other emotions might also contribute to hallucinations [58], including euphoric/serene emotions associated with transient mystical experiences [59].

The current study investigates trait and state indices of susceptibility to hallucinatory imagery by two means: firstly by assaying effects of induced mood and flicker frequency on the quantity and complexity of induced GI and alpha power (lower and upper); and secondly, by relating these cognitive and neurophysiological dependent variables to individual differences implicated in psychosis proneness: self-reported positive schizotypy (propensity for experiencing perceptual anomalies) and vividness of trait mental imagery. Given previous

reports that men maintain visual percepts longer [60] and become more distracted under Ganzfeld conditions [61], and that sex differences are observed in relation to the neurophysiological correlates of positive schizotypy [11], sex differences in the propensity to report GI are also investigated.

We hypothesised a decrease in lower-alpha and increase in upper-alpha under Ganzfeld conditions. Higher propensity for GI would be associated with male sex, high trait mental imagery and positive schizotypy, reduced lower-alpha power and fear induction. We predicted replication of Becker and Elliot's (2006) finding of maximal imagery at 16 Hz flicker frequency.

2. Materials and methods

2.1 Participants

Forty-six participants were recruited from the academic and general population (aged 18-57 mean=24.15 SD=9.26; 16 men). The study was approved by the Nottingham Trent University College of Business, Law and Social Sciences Research Ethics Committee, and subjects gave written informed consent. Participants sat at a desk on a comfortable chair and were instructed to keep as still as possible throughout. Participants received a shopping voucher (£10) and course credits (in the case of students) in remuneration for their time. Prior to experimental measures, participants completed self-report assessments of mental imagery vividness and propensity to experience anomalous perceptions.

2.2 Psychometrics

2.2.1 Positive Schizotypy

The Cardiff Anomalous Perceptions scale (CAPS) [6] - used to assess positive schizotypy/psychosis proneness - is a reliable ($\alpha = 0.87$) 32-item assessment of unusual perceptual experiences (e.g. changes to sensory intensity, distortions of existing perceptions, and hallucinations), with a Yes/No dichotomic format (e.g. “Do you ever hear your own

thoughts repeated or echoed"?) and a range of 0 (low schizotypy) to 32 (high schizotypy). Additional CAPS subscales quantify the frequency, distress and intrusiveness of these anomalous perceptual experiences, but were omitted in the current study due to time constraints.

2.2.2 Trait mental imagery

The 35-item Betts' questionnaire on mental imagery (QMI) [62] measures ability to generate images across seven modalities (visual, auditory, cutaneous, kinaesthetic, gustatory, olfactory, and organic) using a seven-point vividness rating scale. Participants are instructed to visualise from memory an item from a written description, and rate how vivid the image appeared to them using a scale of 1 (perfectly clear) to 7 (no image at all). Scores on this scale were reversed in the current study, so that greater score reflected greater vividness. Internal consistency is high ($\alpha = 0.97$) [33].

2.2.3 Positive and Negative Affect Scale –Expanded

The Positive and Negative Affect Schedule–Expanded Form (PANAS-X) [63] contains 60 items consisting of adjectives that describe feelings or emotions. Participants rate how they feel "right now" (state version) using a five-point scale ranging from 1 (very slightly or not at all) to 5 (extremely). In the current study, participants completed the whole PANAS-X instrument at baseline and after each Ganzfeld mood condition (see below). Average scores for target emotions (*Fear*, *Serenity*) and for *Attention* were calculated.

2.3 Ganzfeld apparatus and task

2.3.1 Photic stimulation apparatus

Ganzfeld exposure was delivered via a purpose-built optical array comprising 300 strip RGB LEDs (DAYBETTER: SMD 5050; approx. peak wave length; R: 625nm, G: 524nm, B: 471nm), mounted on a cardboard panel (51cm wide X 32cm high), set into a reinforced frame. The apparatus was used in conjunction with a pair of plastic light-diffusing goggles

containing opaque lenses. The array was positioned directly in front of participants on a desk (horizontal distance from eyes 39 cm; vertical distance off the desktop 23 cm), and was connected to a custom circuit that took a 3.5mm jack audio voltage level input from a stimulus PC (Windows 7 OS), outputting it as a time series of light levels rather than as sound. Using a transistor (TIP29C) as a switch, an input signal (see below) from the stimulus PC's on-board sound card (Realtek High Definition Audio) was buffered through an operational amplifier (LM324N Quad op-amps) [64] to a 12V DC level capable of driving the LED array at 8 target frequencies (8 Hz, 10 Hz, 12 Hz, 14 Hz, 16 Hz, 20 Hz, 22 Hz, and 24 Hz), chosen for their association with GI [13]. A cathode-ray oscilloscope was used to verify that distortion of the input signal in relation to the commanded light level was minimal. As a result of an unforeseen interaction between OpenSesame and lower-sampling-rate (44.1 kHz) digitisation which was applied to all stimulus square-wave frequencies except 16 Hz, light stimulation frequencies were up-shifted by 8.9%, yielding effective stimulation frequencies of 8.7 Hz, 10.9 Hz, 13.1 Hz, 15.2 Hz, 16 Hz (unaffected), 21.8 Hz, 24 Hz and 26.1 Hz. These shifted frequencies nevertheless accomplished the goal of spanning the intended range. (The 16 Hz stimulus was produced at the commanded frequency because its square wave was digitised at a higher sampling rate of 340 kHz.)

The input signal to the photic stimulation apparatus was managed by custom software implemented in Python, running on the stimulus PC through OpenSesame [65]. The input signal comprised 8 individual time series tracks, one for each target frequency of visual flicker stimulation. Tracks were created using multi-track recording and editing software, and were each 30 seconds in duration. Each track consisted of multiple non-temporally-overlapping square wave forms with a 50/50 duty cycle and period corresponding to the track’s target frequency. Tracks were delivered as a pre-set pseudo-random playlist (supplementary table S1), with each frequency repeated a total of five times per cycle with no temporal overlap between frequencies. The same playlist configuration was used in each Ganzfeld exposure to avoid uneven distribution of frequencies and order effects due to high-to-low, or low-to-high bias. The configuration also ensured that- except for the 5.8 Hz gap between 16 Hz and 21.8 Hz which resulted from the aforementioned systematic discrepancy between commanded and displayed stimulus frequencies- step differences between

neighbouring frequencies did not exceed 4 Hz, as pilot research indicated changes above this value influenced the perception of GI. These constraints precluded counterbalancing the sequence across participants.

In addition to these purely visual light-flicker tracks, Ganzfeld conditions involved exposure to one of three soundscapes piloted for the extent to which they induce target moods *Fear* and *Serenity*, as measured by the PANAS-X. Each soundscape was created using Audacity software, and was 20 minutes and 30 seconds in duration. A control soundscape used pink noise, with a 5-second fade-in and fade-out. Fear and Serenity soundscapes used a combination of commercial music tracks and other sound samples (supplementary tables S2-3), with multiple tracks and/or segments of tracks overlapped using a 5-second fade-in and fade-out. Whilst most tracks used in soundscapes were instrumental, two tracks (n=1 for serenity, and fear) included short snippets of human speech (< 2sec), which were rendered incomprehensible by masking with other sounds. Soundscapes were played to participants in an uncompressed (PCM) audio format through earbud headphones (Sennheiser CX 2.00i). The custom software initiated playback of a specific soundscape at the start of each block using a Media Player on the stimulus PC (via a second sound card; Asus Xonar HDVA 1.3).

2.3.3 Ganzfeld task and instructions

Three Ganzfeld sessions (blocks) were used, each lasting 20 minutes and 30 seconds, with 5-minute intervals taken between blocks. Using the photic stimulation apparatus, in each block participants were exposed to red light-flicker at specific frequencies according to the pre-set, pseudo-random playlist whilst also listening to a soundscape. While the same frequency playlist was repeated for each participant across blocks, a different soundscape (control, serenity, fear) was played to participants within each block. Ganzfeld blocks were counterbalanced across participants, and where a session ended using the Fear soundscape, participants completed a short task at the end of the experiment to void any residual negative affect. The first 30 seconds of each block provided a “settling in” period for participants, during which they heard only the soundscape. After 30 seconds light flicker began. At the end of each block the soundscape and light flicker terminated, and room lighting was restored.

Earphones and goggles were removed from participants, allowing them a short rest break during which they completed the PANAS-X.

Participants were instructed to keep their eyes open (with the exception of blinking) throughout Ganzfeld exposure. The experiment described representative examples of simple images (e.g., geometric shapes; spirals, tunnels, squares, triangles, circles, and chequerboards), and complex images; for example, body parts (e.g., arms, legs eyes, hands), animals (e.g., cat, dog, bird), humanoid figures (distinct or cartoonish), and scenery (e.g., landscapes, cityscapes). Participants were also told that images different from the examples given might be seen, to reduce priming effects.

In each block, participants were asked to rest their fingers across 4 buttons and indicate by button-press the onset of any simple (static or moving) or complex (static or moving) image, or if the image changed. Following each button press, participants were required to count silently for two seconds before describing, in as few words as possible, what it was they perceived. Trigger codes sent to the recording computer were used to calculate the number of reports of simple and complex images as a function of flicker frequency and mood induction condition. To reduce data, static and moving images were collapsed at the point of scoring. Throughout Ganzfeld exposure, descriptions of any shapes/images reported by participants were recorded manually by the experimenter and via a digital voice recorder. Descriptions were used as a basis for a follow-up qualitative interview with a subsample of participants (not included in the current study).

2.4 Electroencephalographic assessment

Using a 64-channel ActiveTwo acquisition system (BioSemi, Amsterdam, Netherlands), EEG was sampled at 2048 Hz and digitised at 24 bits. Data were collected reference-free using ActiView V 6.05 (National Instruments, TX, USA). Curry v8S software [66] was used for signal processing of continuous EEG. Offline, data were processed separately for each mood condition. Pre-processing included referencing to the algebraic average of all electrodes and baseline correction. Data were then bandpass filtered (0.5 Hz-70 Hz, Hann function,

width=10%) with a 50 Hz notch filter. Principal components analysis was used for ocular artefact reduction. Five 30-second epochs were defined over each combination of conditions and flicker frequency (e.g., 5 x 8.7 Hz fear), and concatenated into continuous data (at least 2.5mins) for each condition. Each of these was sub-epoched (back-to-back) at 2 sec/epoch. Epochs containing residual artefact were then identified using a semi-automated procedure and removed from analysis.

Lower-alpha and upper-alpha were calculated using an individual subject-specific alpha bands and individual widths method, shown to be more robust than the fixed frequency, fixed band approach [67]. To this end, for each 2s epoch, a Fourier transform spanning the entire epoch (2048 bins, 1/2Hz per bin) was used to calculate power at .5Hz steps between 7.5Hz and 12.5Hz. Power was then averaged across all epochs. The weighted mean method was then used to identify the individual peak alpha frequency (IAF). An FFT (across 2 sec epochs/condition) was then applied to the data based on individual bandwidths for lower- and upper-alpha. Lower-alpha was calculated as (IAF*.8) to IAF. Upper-alpha was calculated as IAF to (IAF*1.2).

2.5 Planned Statistical Analysis

Validity of the mood induction procedure was verified by repeated-measures analyses of variance (ANOVA) testing the effect of *mood induction* (Fear, Serenity, Pink Noise) on PANAS scores for Fear, Serenity and Attention. Repeated-measures ANOVA was also used to test the effects of *mood induction*, *flicker frequency* and *image complexity* (Simple, Complex) on the number of images reported. Further repeated-measures ANOVA was used to test neurophysiological effects of *mood induction*, *flicker frequency*, and *electrode hemisphere* (Left, Right) on alpha power; because equality of variances across recording sites and alpha frequency bands could not be assumed, these tests were conducted separately for frontal (F3, F4) and occipital (O1, O2) sites and for lower and upper-alpha bands. Greenhouse-Geisser correction was applied where sphericity could not be assumed. Whilst only 4 electrodes (representative of anterior and posterior bilateral sites) were used so as to simplify statistical

analysis, topographic maps and frequency plots are presented in Figure 3 for a more detailed view of data from all channels.

Pearson correlations were used to test the relationship between number of images reported (simple, complex), psychometric measures (CAPS scores, trait mental imagery) and alpha power (lower, upper). In these analyses, to minimise multiple comparisons, the mean frontal power was estimated using the mean of sites F3 and F4 across all flicker frequencies, and occipital power using the mean of O1 and O2. Separate scores were calculated for lower- and upper-alpha. Thus, the following EEG variables were included in the correlation: Frontal lower-alpha, Frontal upper-alpha, Occipital lower-alpha, and Occipital upper-alpha.

3. Results

An outlier, who reported over 500 images, was excluded from analyses of GI. Table 1 shows means and standard deviations of PANAS scores (Fear, Serenity, and Attentiveness) as a function of *Mood Induction* condition. Table 2 shows means and standard deviations for psychosis proneness, mental imagery, number of images reported (simple, complex), lower-alpha power (frontal, occipital) and upper-alpha power (frontal, occipital). Figure 1 shows the number of images reported as a function of *Mood Induction* and *Flicker Frequency*. Figure 2 presents mean lower and upper-alpha power at frontal and occipital sites as a function of *Mood Induction* and *Flicker Frequency*.

[Please insert Tables 1 and 2 about here]

3.1 Validation of subjective Mood Induction

Repeated-measures ANOVA showed significant effects of *Mood Induction* (Fear, Serenity, Pink noise) for PANAS-X scores of Fear [$F(2,88)=17.54$, $p<.001$,$\eta^2=.29$] and Serenity [$F(2,88)=21.05$, $p<.001$,$\eta^2=.32$], but not attentiveness. PANAS-X Fear scores after Fear induction exceeded those after Pink noise [$F(1, 44)=18.21$, $p<.001$, $\eta^2=.29$] and Serenity induction [$F(1, 44)=21.38$, $p<.001$,$\eta^2=.33$]. PANAS-X Serenity scores after Serenity induction

exceeded those after Pink noise [F(1, 44)=12.57, p<.001, η^2=.22] and Fear induction [F(1, 44)=39.34, p<.001,η^2=.47].

3.2. Effect of sex on number of images reported

Men reported more images (Simple mean=31.14, sd=41.58; Complex mean=21, sd=26.56) than women (Simple mean= 11.80, sd=12.49; Complex mean=7.73, sd=10.02) [multivariate F(1, 41)=4.69, p=.015,η^2=.19; Simple F(1, 42)=5.55, p=.023, η^2=.12; Complex F(1, 42)=5.84, p=.020, η^2=.12].

3.3. Effect of Mood Induction and Flicker Frequency on number of images reported

Repeated-measures ANOVA with *Mood Induction* (Fear, Serenity, Pink noise), *Flicker Frequency* (8.7–26.1 Hz) and *Image Type* (Simple, Complex) as within-groups variables showed a significant main effect of *Flicker Frequency* on number of images reported [F(7, 308)=8.64, p<.001,η^2=.16] (Figure 1). There was a significant increase in reports between 15.2 Hz and 16 Hz [F(1,44)=4.71, p=.036,η^2=.10], followed by a drop between 16 Hz and 21.8 Hz [F(1,44)=6.37, p=.015,η^2=.13] and between 21.8 Hz and 24 Hz [F(1,44)=15.77, p<.001,η^2=.26]. There were no effects of *Mood Induction* or *Image Type*, and no interactions (all p>0.05).

3.4. Effect of mood induction and flicker frequency on alpha power

Repeated-measures ANOVA was used to investigate the effect of *Flicker Frequency* (8.7–26.1 Hz) and *Mood Induction* (Fear, Serenity, pink noise) on alpha power separately for lower- and upper-alpha at bilateral frontal (F3, F4) and occipital (O1, O2) electrode sites (Figure 2).

There was a significant effect of *Mood Induction* on frontal lower-alpha [F(1.93, 84.99)=3.70, p=.030, η^2=.08], frontal upper-alpha [F(1.91, 85.90)=4.30, p=.018, η^2=.09], occipital lower-alpha [F(1.92, 84.52)=3.27, p=.043, η^2=.07], and occipital upper-alpha [F(1.98, 89.25)=6.49, p=.002, η^2=.13], such that lower power was seen in the Fear condition, relative to Noise

[frontal lower F(1, 44)=6.38, p=.015, η^2=.13; frontal upper F(1, 44)=7.10, p=.011, η^2=.16; occipital lower F(1, 44)=6.09, p=.018, η^2=.11; occipital upper F(1, 44)=9.87, p=.003, η^2=.18], and Serenity [frontal lower trend only F(1, 44)=2.37, p=.13, η^2=.05; frontal upper trended only F(1, 44)=3.81, p=.57, η^2=.08; occipital lower F(1, 44)=4.39, p=.04, η^2=.09; occipital upper F(1, 44)=9.75, p=.003, η^2=.18]. No significant interaction effects involving Mood induction were found for lower or upper-alpha power.

There was a significant effect of *Flicker Frequency* for all power measures [frontal lower-alpha F(2.66, 116.86)=11.58, p<.001, η^2=.21; frontal upper-alpha F(3.94, 177.39)=48.66, p<.001, η^2=.52; occipital lower-alpha F(3.10, 136.37)=12.49, p<.001, η^2=.22; occipital upper-alpha F(3.70 166.52)=56.53, p<.001, η^2=.56].

Less lower-alpha power was evoked at the mid-frequency flicker stimulation ranges [13.1 Hz, 15.2 Hz, 16 Hz] and greatest power in the lower-alpha range at the lowest (8.7 Hz) and highest (24 Hz, 26.1 Hz) flicker frequencies. Similarly, in the upper-alpha band, an increase in power was seen at 10.9 Hz compared to 8.7 Hz flicker frequency, followed by a drop at 13.1 Hz, 15.2 Hz and 16 Hz flicker and a second rise for the faster flicker frequencies (21.8 Hz, 24.0 Hz, 26.1 Hz). Thus, highest upper-alpha power values were seen for 10.9 Hz, 21.8 Hz, 24.0 Hz, 26.1 Hz flicker frequencies. Table 3 displays statistical values for significant post-hoc comparisons.

3.5. Correlation Analysis

CAPS scores and numbers of simple and complex images reported all failed a test for normality (Shapiro-Wilk test) and underwent logarithmic transformation to approach normality, yielding transformed simple image count (skewness=-.14, kurtosis=.-.83), complex image count (skewness=-.08, kurtosis=.-.86), and CAPs (skewness=-.30, kurtosis=.-.88). Correlation analysis is shown in Table 4. Following Hochberg correction for multiple comparisons, the number of images reported was positively correlated with CAPS score and negatively correlated with occipital lower-alpha. Occipital lower-alpha was negatively

correlated with CAPS score. Weaker inverse associations between upper-alpha power and these variables did not survive correction for multiple comparisons.

3.5. Frequency plots and topographic maps

Figure 3 shows frequency plots of power and topographic maps for lower alpha band (8-10Hz), upper alpha band (10-12Hz) and SSR, as a function of *Flicker Frequency*, collapsed across all *Mood Induction* conditions. Within the figure, endogenous alpha and SSR can be distinguished. SSR is occurring at the stimulation frequency. SSR harmonics are seen at twice the frequency of SSR. Topographic maps show a bilateral occipital distribution for endogenous alpha, whilst the SSR is more medially distributed. (To avoid confounding exogenous SSR with endogenous alpha in overlapping frequency bands, SSR maps for 8.7 Hz and 10.9 Hz flicker show the topographic map of the second harmonic, 17.4 Hz and 21.8 Hz respectively).

3.6. Can findings be explained by differences between stimulation frequencies in blink rate?

In order to explore whether the effects might be due to differences across stimulation frequencies in blink rate, the number of blinks was counted for each stimulation frequency in the fear condition. Mean blinks for each frequency are as follows: 8.7 Hz = 23.09; 10.9 Hz = 28.91; 13.1 Hz = 29.69; 15.2 Hz = 28.89; 16.0 Hz = 28.96; 21.8 Hz = 29.91; 24.0 Hz = 31.20; 26.1 Hz = 31.87. The mean number of blinks during higher stimulation frequencies (24.0 Hz, 26.1 Hz) was slightly higher than the lower frequencies. However, a within subjects ANOVA showed that this was only significant in comparison to 8.7 Hz (which had significantly lower blink rate than all other frequencies) [e.g., 8.7 Hz < 10.9 Hz $F(1,44)=25.21$, $p<.001$]. Pearson correlation showed that total blinks were inversely related to the number of complex images reported ($r=-.33$, $p=.027$), but was not related to number of simple images reported, CAPS, mental imagery or any of the total alpha measures (frontal lower, frontal upper, occipital lower occipital upper). Therefore, it is unlikely that differences in blink rate between stimulation frequencies can explain the differences in alpha power, at least not for the blink rate during fear condition.

4. Discussion

The current study had two goals: first, to investigate subjective reports of simple and complex flicker-induced images, as well as the neurophysiological response (lower- and upper-alpha power), as a function of light-flicker frequency and mood induction; and second, to test the relationship between alpha power and i) propensity to report GI (state) and ii) psychometric traits associated with propensity to hallucinate - positive schizotypy (CAPS) and trait mental imagery. The main findings were:

1) Greatest propensity to report images was seen at lower stimulation frequencies, particularly 16 Hz for simple images, with lower likelihood at higher frequencies (21.8, 24, 26.1 Hz).
2) Occipital lower-alpha power was inversely correlated with CAPS scores and the number of images (simple and complex), even after correction for multiple comparisons.
3) Association between upper-alpha power and propensity to hallucinate (psychometric scores and number of GI reported) was weaker than with lower-alpha, and did not survive correction for multiple comparisons.
4) The expected SSR was observed close to the frequency of stimulation.
5) Alpha power was lowest for lower flicker frequencies. This effect is obscured in the statistics for 8.7 Hz and 10.9 Hz flicker frequencies due to the overlap between alpha and the SSR at these stimulation frequencies, but is apparent in Figure 3.
6) Fear induction is associated with reduction in alpha power. Whilst the pattern of results was in the anticipated direction for the effect of fear induction on the number of complex images reported, this effect was not significant.
7) CAPS was positively associated with the propensity to report simple and complex images; Associations between mental imagery and the number of images reported did not survive correction for multiple comparisons.
8) Men reported more images than women.

Consistent with our hypothesis, the number of GI reported was associated with a reduction in lower-alpha power, but not with an increase in upper-alpha power. This finding supports a

growing literature on functional differentiation of alpha sub-bands [39, 40]. It is possible that reduced lower-alpha power is an epiphenomenon, i.e., related to the light flicker Ganzfeld experimental conditions, but not casually related to the appearance of GI. However, corroborating evidence from state and trait aspects of the current study, along with reports of reduction in alpha power in psychosis [44-47], oppose this idea. Current findings are also in line with Beck et al. (2009) who report a decrease in lower-alpha (8-10 Hz) power prior to the onset of hallucinatory colour [41].

Given the association of reduced lower-alpha with psychosis proneness, but not trait mental imagery, this neurophysiological response seems unlikely to reflect top-down processes *per se*. The lower-alpha band has been proposed to reflect mechanisms underpinning active inhibition of cortical activity, such as mechanisms involved in attentional suppression and inhibition, or filtering out "stimulus-irrelevant" information [68]. Thus, less alpha power over the occipital region may indicate destabilisation of cortical activity for visual perception.

Keitel et al. (2014) differentiated endogenous alpha (9-10 Hz) from the SSR, in response to stimulation frequency just above 10 Hz [69, 71]. Although we did not statistically delineate the SSR from alpha, topographic maps suggest a more midline focus of SSR (and its second harmonic), and more lateral distribution for alpha (Figure 3). In comparison to the focal occipital maxima for SSR observed by Keitel and colleagues, the maxima for SSR (and its harmonics) in the current study extended more anteriorly to parieto-occipital midline.

The presence of the SSR likely accounts for the increase in power in the lower-alpha range at 8.7 Hz stimulation, and in the upper-alpha range at 10.9 Hz stimulation. The presence of subharmonics for 21.8 Hz, 24 Hz and 26.1 Hz flicker may have contributed to higher alpha power at these stimulation frequencies compared to 13.1 Hz, 15.2 Hz and 16 Hz. However, given that the subharmonic is of very low power compared to the difference seen in alpha power between the upper and lower stimulation frequencies (Figure 3), it seems unlikely to fully explain this effect. Whilst we did not directly assess the association between the SSR and propensity to report GI, others have suggested reduced SSR in people with schizophrenia during 17 Hz and 23 Hz stimulation [72]. 16 Hz was not investigated in that study. Thus,

future work should delineate SSR and alpha more precisely, and examine any independent contribution of the SSR to propensity to report GI.

The relationship between reduced lower-alpha power, number of GI reported and flicker frequency does fit with the known characteristics of the human visual system's response to stimuli of varying temporal frequency. The magnitude of response to flicker stimulation varies according to several factors, including spatial frequency, luminance, motion, and temporal frequency (e.g., [73-76]). Depending on the levels of these factors, peak sensitivity typically lies between 8–18 Hz, tending towards the higher end of the range for stimuli of low spatial frequency [77], including those used here (equivalent to 0 cycles per degree, or infinitely low spatial frequency). Thus, SSRs tend to be of greatest power within this range compared to upper stimulation frequencies (21.8 Hz, 24 Hz, 26.1 Hz). This appears to coincide with the interval of greatest cortical destabilisation (lowest alpha power) and highest propensity to report GI. If in the absence of any clearly defined source, visual cortex is most likely to produce GI under conditions of maximum stimulation [78], this tendency would predict the pattern we observed, with high SSR and low alpha suggesting a state of cortical excitability and destabilisation. This hypothesised link warrants further investigation in studies integrating Ganzfeld, EEG and visual psychophysics modalities.

Consistent with current findings, at least two other studies have reported the greatest propensity for image induction due to light-flicker as ranging between 10 and 16 Hz [38, 79]. However, whilst lower-alpha tended to be reduced across these flicker frequencies, with a node around 12 Hz, the number of simple images showed a sharp increase at 16 Hz. Together with evidence from a previous study showing reductions in lower-alpha prior to the onset of hallucinatory colour [41], the current results are in line with the idea that reduced lower-alpha does not merely reflect an attentional response to the appearance of the GI, but rather a prior neurophysiological context conducive to GI, that is, cortical destabilisation. Additional mechanisms (not currently measured) that respond more specifically to 16 Hz flicker likely underpin the sharp increase in propensity for GI at this stimulation frequency, and should be determined by further research. Candidates include mechanisms reflected by synchronisation

of gamma activity thought to underpin the binding of sensory information and feature encoding [80].

Whilst the pattern of results for complex images lay in the anticipated direction, the current data indicate that the induced affective states did not significantly impact the production of GI *per se*. However, fear induction was associated with a significant reduction in alpha power (upper and lower). It is possible that, although the soundscapes currently used were able to induce target moods sufficiently to alter alpha power, arousal in response to these moods might not have been sufficient to affect subjective experience. Future studies measuring arousal should investigate ways to induce more intense moods and whether emotion modulates the GI content, as is the case with hallucinations [81], rather than just the number of images produced. Future studies should also directly compare different types of Ganzfeld, given that the static (compared to flicker) Ganzfeld tends to produce more complex images, of sometimes oneiric quality across multiple sensory modalities, although after a longer latency. Whether mood effects the latency, quality or frequency of static Ganzfeld images warrants investigation. Finally, in order to reduce the complexity of data, we collapsed responses for static and moving images. However, future studies might compare these and other qualities of the images.

Sex differences in reports of GI suggest that networks mediating the induction of images may be more readily disrupted by light flicker Ganzfeld conditions in men relative to women. This result is consistent with literature, suggesting sex differences in schizophrenia spectrum disorders (e.g. [82, 83]). For example, men tend to suffer earlier onset of schizophrenia, and distinct neurobiological networks might underpin positive symptoms in men compared to women [11, 84]. Although women with schizophrenia are more likely to report symptoms of reality distortion relative to men [85], underpinning mechanisms associated with psychosis in women, such as right frontal function [11], may be less affected by Ganzfeld.

Conclusions

The current research supports reduced lower-alpha power, but not upper-alpha, as conducive to perceptual anomalies and GI, and posits other mechanisms occurring in response to 16 Hz

flicker (greatest simple GI propensity) with the onset of the percept. Associations between GI, reduced lower-alpha and positive schizotypy support light-flicker Ganzfeld as an experimental model of psychosis proneness which might be particularly relevant to men. Whilst fear induction did not significantly increase GI, it did result in reduced alpha power; further work is needed to better understand the GI response to emotions. Findings have implications for understanding the neurophysiological mechanisms underpinning predisposition to perceptual anomalies in the context of Ganzfeld and in a subpopulation defined by psychosis proneness.

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Declaration of interest

Conflict of interest: none.

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Figures

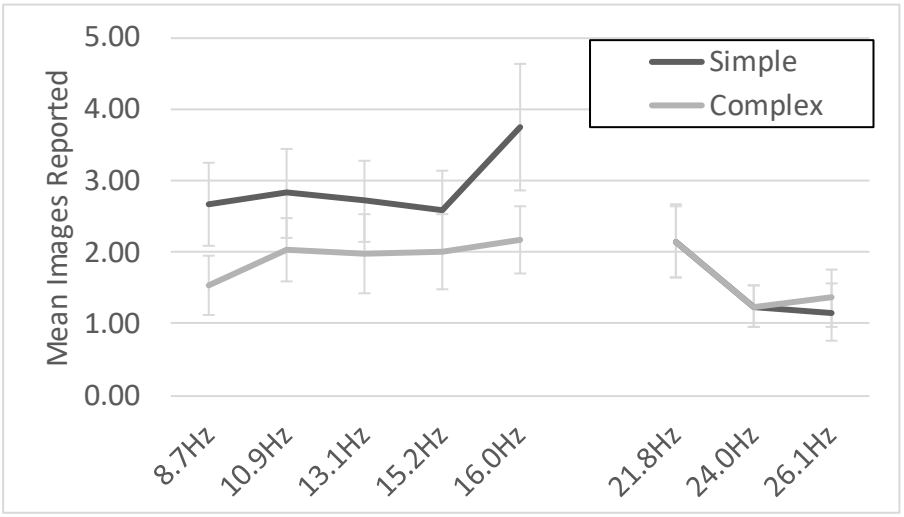

Figure 1. Mean number of simple and complex images reported as a function of Flicker Frequency.

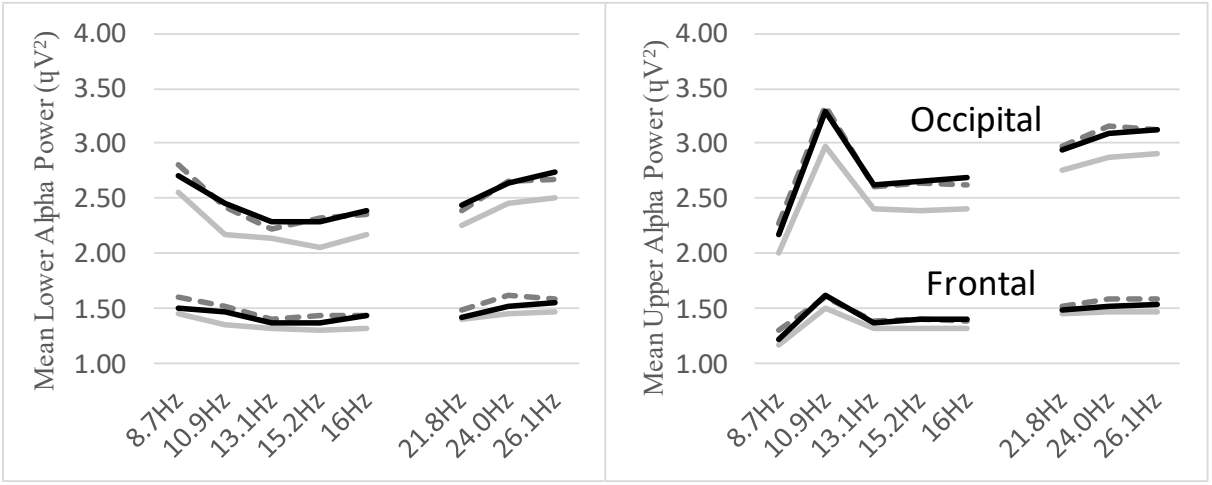

Figure 2. Mean lower- and upper-alpha power as a function of Mood Induction and Flicker Frequency at frontal and occipital sites (mean of left and right hemispheres; Black=Serenity, Grey=Fear, Dashed=Noise). N.B. Mean alpha scores are across 5 bins (i.e. multiply by 5 for total power).

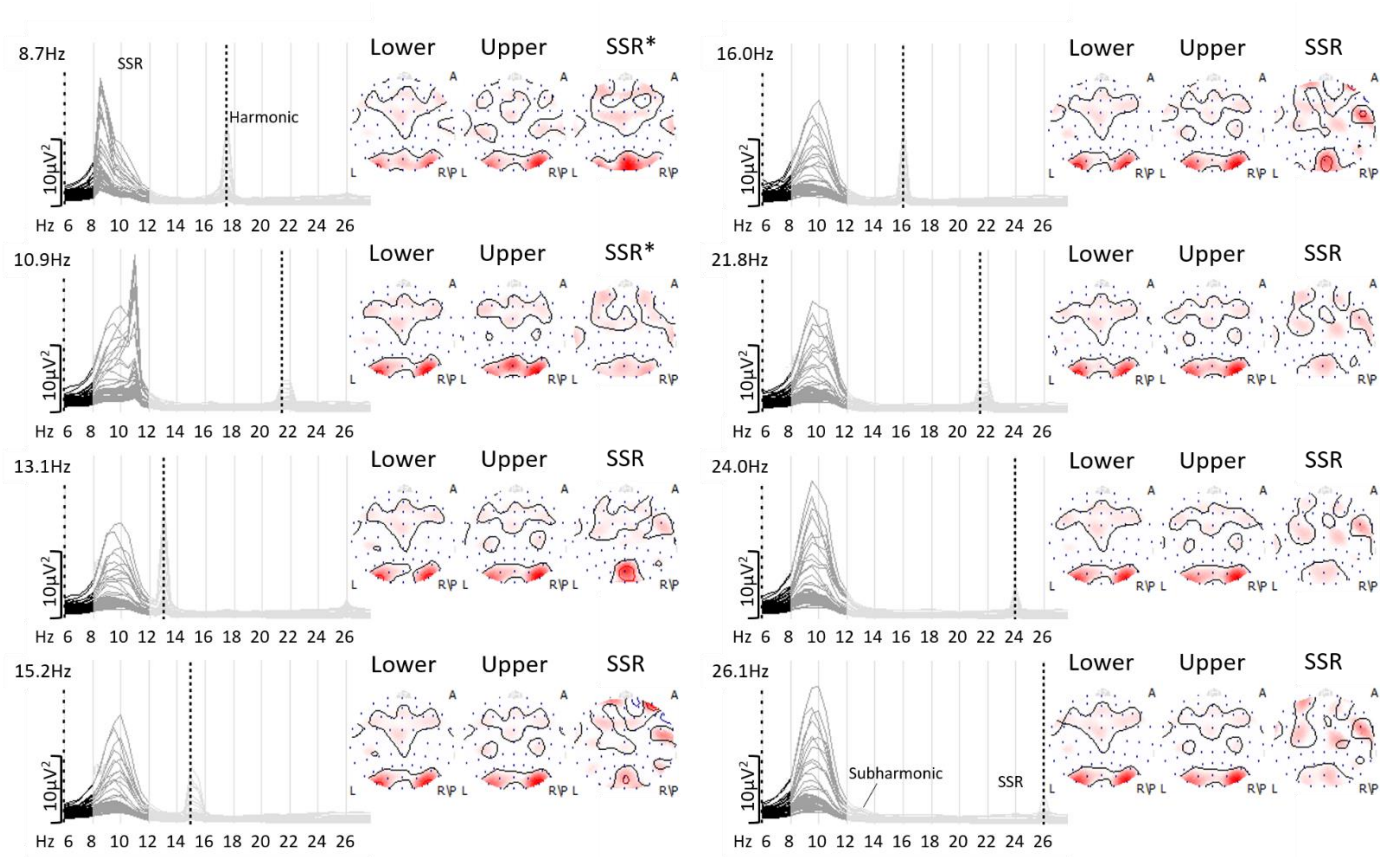

Figure 3. Fourier transform and topographic maps for alpha power and steady-state response (SSR), as a function of flicker frequency.

**To avoid confounding exogenous SSR with endogenous alpha in overlapping frequency bands, SSR maps for 8.7 Hz and 10.9 Hz flicker frequencies are shown for the second harmonics.*

Table 1. Means and standard deviations of PANAS scores (Fear, Serenity, Attentiveness) as a function of Mood Induction condition.

	Mood Induction Condition					
	Fear		Serenity		Noise	
PANAS	Mean	SD	Mean	SD	Mean	SD
Fear	1.87	0.84	1.30	0.51	1.42	0.52
Attentiveness	2.69	0.87	2.75	0.91	2.57	0.93
Serenity	2.40	1.00	3.44	0.89	2.86	1.04

Table 2. Means and standard deviations of number of images reported, mental imagery, CAPS, and mean alpha power at frontal and occipital sites.

	Mean	SD
Simple Images Reported	19.60	27.35
Serenity	6.33	8.52
Fear	6.38	9.48
Noise	6.89	10.96
Complex Images Reported	14.87	18.77
Serenity	4.31	7.49
Fear	5.84	6.52
Noise	4.71	6.40
Mental Imagery	145.98	23.91
CAPS	6.89	6.16
Occipital Lower-alpha	2.45[a]	0.14
Occipital Upper-alpha	2.75 [a]	0.16
Frontal Lower-alpha	1.45 [a]	0.08
Frontal Upper-alpha	1.43 [a]	0.07

[a]mean across 5 bins (i.e. multiply by 5 for total power)

Table 3. Significant effects from analysis of variance post-hoc tests for stimulation frequency comparisons on lower and upper alpha at frontal and occipital sites

	Comparison	F	df	p	η^2
Lower alpha					
Frontal					
	10.9 Hz > 13.1 Hz	17.95	1,44	<.001	.29
	16.0 Hz < 21.8 Hz	4.19	1,44	.047	.09
	21.8 Hz < 24.0 Hz	38.92	1,44	<.001	.47
Occipital					
	8.7 Hz > 10.9 Hz	6.51	1,44	.014	.13
	10.9 Hz > 13.1 Hz	6.0	1,44	.018	.12
	15.2 Hz < 16.0 Hz	5.07	1,44	.029	.10
	21.8 Hz < 24.0 Hz	52.90	1,44	<.001	.55
Upper alpha					
Frontal					
	8.7 Hz < 10.9 Hz	119.44	1,44	<.001	.73
	10.9 Hz > 13.1 Hz	74.11	1,44	<.001	.62
	16.0 Hz <21.8 Hz	22.70	1,44	<.001	.34
	21.8 Hz < 24.0	7.52	1,44	.009	.14
Occipital					
	8.7 Hz < 10.9 Hz	106.35	1,44	<.001	.70
	10.9 Hz > 13.1 Hz	65.51	1,44	<.001	.59
	16.0 Hz < 21.8 Hz	30.37	1,44	<.001	.40
	21.8 Hz <24.0 Hz	22.83	1,44	<.001	.34

Table 4. Correlations between number of images reported (simple and complex), psychometric scores (Mental Imagery, CAPS) and alpha power.

		Images reported		Mental	
		Simple [b]	**Complex** [b]	**Imagery**	**CAPS** [b]
Complex Images Reported [b]		**.63*****			
Mental Imagery		.35	0.29		
CAPS [b]		**.49****	**.47****	-.05	
Lower-alpha					
	Frontal	-.21	-.27	.17	-.21
	Occipital	**-.40***	**-.37***	.02	**-.37***
Upper-alpha					
	Frontal	-.15	-.17	.17	-.14
	Occipital	-.31	-.26	.04	-.25

[b] Variable (+1) ln transformed to approach normal distribution

Following Hochberg correction ***p<.001; **p<.01; *p<.05

Supplementary material

Tables

S1. Input sequence used in Ganzfeld sessions.

Position	Input track	Position	Input track	Position	Input track
1	8 Hz	**16**	8 Hz	**31**	12 Hz
2	12 Hz	**17**	12 Hz	**32**	8 Hz
3	10 Hz	**18**	8 Hz	**33**	12 Hz
4	14 Hz	**19**	10 Hz	**34**	8 Hz
5	16 Hz	**20**	14 Hz	**35**	10 Hz
6	20 Hz	**21**	16 Hz	**36**	14 Hz
7	22 Hz	**22**	20 Hz	**37**	16 Hz
8	24 Hz	**23**	22 Hz	**38**	20 Hz
9	22 Hz	**24**	24 Hz	**39**	22 Hz
10	24 Hz	**25**	22 Hz	**40**	24 Hz
11	20 Hz	**26**	24 Hz		
12	16 Hz	**77**	20 Hz		
13	14 Hz	**28**	16 Hz		
14	10 Hz	**29**	14 Hz		
15	12 Hz	**30**	10 Hz		
Number of Repeats per session: 8Hz, *n*=5; 10 Hz, *n*=5; 12Hz, *n*=5; 14Hz, *n*=5; 16Hz, *n*=5; 20Hz, *n*=5; 22Hz, *n*=5; 24Hz, *n*=5.					

S2. Track listings for Serenity Soundscape.

Track No.	Name	Artist	Notes
	Sea waves crashing on a shale beach	John Anderson	Binaural recording (mixer)
1	A seated Knight https://soundcloud.com/moby/a-seated-night-ambient	Moby	
2	Enjoy The Moment (Unquote Remix) https://soundcloud.com/unquote/bop-enjoy-the-moment-unquote-remix	Bop	
3	Gymnastics https://soundcloud.com/ganga/ganga-versus-erik-satie	Ganga & Erik Satie	
4	Focus (Seacrofts Chilled Experience) https://www.beatport.com/track/focus-seacrofts-chilled-experience/1988837	Prajex	
5	Going Wrong https://www.amazon.co.uk/Going-Wrong/dp/B00FBWZVSI	Moby	

S3: Track listings for Fear Soundscape.

Track No.	Name	Artist	Notes
	Various sound effects, including: scream sounds sampled from a local Fair and horror event	John Anderson	Binaural recording (used as mixers)
2	Spacecore (sample) https://soundcloud.com/cassio-peia	Cassio Peia	
	Don’t Shuffle (John Andersons max fear mix)	My Teddy Eats Children	
3	Shell IV	Xivalv	
4	Descent	Xivalv	