Minimal exposures reveal visual processing priorities

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ABSTRACT

Human vision is sensitive enough to detect a single photon, but the minimal exposure required to extract *meaning* from stimulation – arguably the visual system's function – remains unknown. This requirement cannot be characterised in terms of stimulus energy, because the system is differentially sensitive to attributes that are distinguished by stimulus configuration rather than physical amplitude. Observers can extract large amounts of information from brief displays; but for given display durations, certain types of information are discerned more readily than others, suggesting that visual pathways prioritise certain stimulus properties. Determining the *minimal* exposure durations required for processing various aspects of a visual stimulus can thus shed light on the system's priorities. Technical limitations have so far prevented measurement of such minima; here, we used a novel technique enabling arbitrarily brief displays with microsecond-level precision to establish the minimal durations required for processing human faces, a stimulus category whose perception is associated with several well-characterised behavioural and neural markers. We found that neural and psychophysical measures converged to reveal a sequence of distinct minimal exposures required for object-level detection (1-2 ms), face-specific processing (3-4 ms), and emotion-specific processing (4-5 ms). Our findings resolve debates about factors that may facilitate processing: Face orientation affected minimal exposure, but emotional expression did not. Awareness emerged with detection; we found no evidence of subliminal perception. These findings critically inform theories of visual processing and awareness by elucidating the information to which the visual system is attuned.

INTRODUCTION

Human vision is extremely sensitive – it is capable of detecting as little as a single photon[1,2]. But the minimal exposure required to extract *meaning* from stimulation – arguably the visual system's function – remains unknown. The more sensitive the visual system is to a visual feature, the less exposure to this feature should be

required to process it. Measuring the minimal exposures that are required to perceive different stimulus properties can therefore reveal whether the presence of certain features facilitates processing[3–7] and whether such facilitation is limited to the feature in question or boosts processing of the stimulus as a whole[3,4,8]. Furthermore, minimal exposures can capture the functional and neural distinction between subliminal and supraliminal processing, by comparing the durations required for explicit measures of awareness to those required for objective perceptual judgments and stimulus-evoked neural activity. This can critically inform theories of consciousness, which differ as to whether they propose that awareness arises simultaneously for all aspects of a stimulus. The prominent global neuronal workspace theory (GNWT), for example, postulates the concept of 'ignition'[9,10], whereby once a stimulus reaches the threshold for conscious detection, information about it is shared across the brain. This implies that all stimulus attributes become available to awareness together, predicting a single minimal required exposure for all attributes. In other theoretical formulations (e.g., recurrent[11] and predictive[12] processing, and recent modifications of the GNWT[13]), subjective experience may arise independently for different attributes of the same stimulus; such views can also accommodate the possibility that higher-level processing may occur subliminally, and imply that for any given attribute, the minimal exposures required for detection, identification, and awareness may differ.

Here, we measured minimal required exposures by finding the shortest display duration that evokes behavioural and neural indices of processing. To date, measurement of such minima has not been possible, as even the briefest presentations offered by current standard displays (~7-16 ms) are not sufficiently brief to prevent detection and identification of complex images. To circumvent this limitation, researchers have employed masking techniques, which disrupt visual processing and can prevent awareness. However, masking confounds processing of the masked stimulus with processing of the mask and with stimulus-mask interactions, making it impossible to determine the minimal exposure required for perceptual processing of individual stimuli.

We used a newly-developed LCD tachistoscope that enables extremely fast, highly-precise visual presentations (**Supplementary Note 1** and **Supplementary Fig. 1**)[14]. This enabled us to present stimuli for arbitrarily brief durations, without masking, and measure the durations required to process various aspects of these stimuli. We used a stimulus category that conveys a wealth of information in human social life: human faces. Importantly, face processing is associated with a host of well-characterised behavioural and neural markers whose presence can be used to assess whether various aspects of a face are processed, and whether this processing happened consciously or subliminally.

Previous studies have suggested a processing advantage and faster access to awareness for upright over inverted faces[15–20], and for emotional over neutral faces[21,22]. (Although the latter claim, in particular, has been challenged[23–26]). If so, processing – and possibly awareness – of upright and emotional faces should require shorter minimal exposures than inverted and neutral faces, respectively.

RESULTS

Psychophysical measures of minimal required exposures

We first investigated these hypotheses psychophysically: In Experiment 1, 32 observers were shown brief displays consisting of an intact face (upright or inverted) on one side of fixation, and its scrambled counterpart on the other side. Intact faces had either a fearful or neutral expression (**Supplementary Note 2** and **Supplementary Fig. 2-3**). Each display was shown for one of seven equally-spaced durations (range 0.8–6.2 ms). After stimulus offset, participants reported the intact face's location and expression with a single keypress; next, they rated their subjective experience of the display using the four-point perceptual-awareness scale (PAS; **Fig. 1A**).

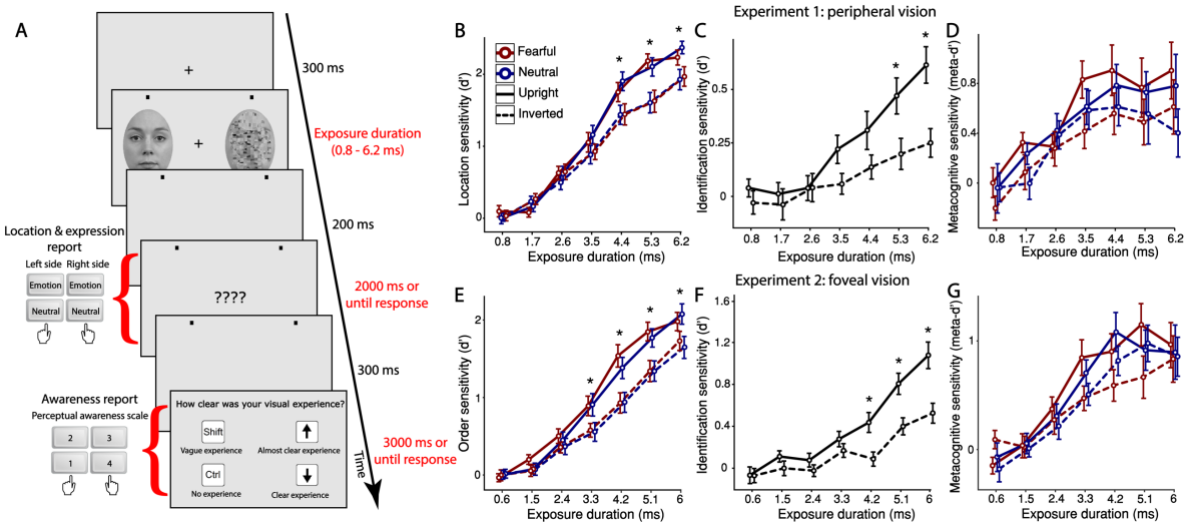

Fig. 1. Schematic trial procedure and psychophysical measures of location, emotion identification, and metacognitive sensitivity. (A) Experiment 1: An intact and scrambled face were presented for one of seven possible exposure durations (range 0.8 – 6.2 ms). Participants pressed one key to report both the location (left or right) and expression (emotional or neutral) of the intact face. Next, they reported the clarity of their visual experience. (B-G) Top: **Experiment 1** (peripheral vision). Bottom: **Experiment 2** (Foveal vision). All measures increased with exposure duration. (B) Location and (E) Order sensitivity departed from chance-level around 2 ms. A significant upright-face advantage (FIE) was present from ~3-4 ms of exposure. (C) and (F) Emotion identification sensitivity showed a significant FIE from ~4-5 ms of exposure. (D) and (G) Metacognitive sensitivity showed an overall FIE, suggesting that upright faces required briefer exposures to reach awareness. Error bars: ±1 SEM. * p<0.05 for upright-inverted comparisons.

Location sensitivity increased with exposure duration, spanning chance-level (d'≈0) to high sensitivity ($F_{(1.99,\,61.97)} = 215.135, p < .001$), (**Fig. 1B**). Detection of intact faces rose above chance at 1.7 ms for all images (one-sample t-tests against zero; all $t(31) > 2.47, p < .002$) except upright fearful faces, which required 2.6 ms ($t(31) = 7.66, p < .001$). An overall advantage for upright over inverted faces ($F_{(1,\,31)} = 34.198, p < .001$) interacted with exposure duration ($F_{(4.9,\,151.98)} = 15.331, p < .001$), arising at exposures of 4.4 ms and above. This upright-face advantage, known as the face-inversion effect (FIE), is considered a marker of configural or holistic processing, where dedicated mechanisms (attuned to upright-canonical face

orientations) integrate facial features[15-17]. Interestingly, the FIE arose at a longer exposure than required for above-chance intact-face detection, suggesting that holistic processing is distinct from basic detection of the face as an intact object. Notably, emotional expression did not affect detection: there was a slight, non-significant advantage for neutral faces ($F_{(1, 31)} = 3.633, p = .066$), with a Bayes Factor indicating strong evidence for the null ($BF_{01} = 10.571$); fearful faces thus conferred no advantage for face detection (see **Extended Data Fig. 1A** for response bias results; also see **Supplementary Note 3** for full report on Experiment 1).

Emotion identification (sensitivity to the presence of a fearful expression) also increased with exposure duration ($F_{(4.2, 130.9)} = 12.89, p < .001$), (**Fig. 1C**; see **Extended Data Fig. 1B** for identification criterion results). An effect of face orientation ($F_{(1, 31)} = 19.54, p < .001$) interacted with exposure duration ($F_{(4.8, 147.2)} = 3.12, p = .012$): an emotion FIE (a marker of emotion-specific processing[27]) arose at durations of 5.3 ms and more. The emotion FIE thus arises at longer exposures than the location FIE, suggesting that less information is required for holistic face processing than for emotion processing.

We used meta-d′ to assess metacognitive sensitivity[28] – the correspondence between participants' location performance and PAS reports – as a proxy measure of awareness[29]. Metacognitive sensitivity increased with duration ($F_{(3.7, 114.4)} = 12.922, p < .001$), rising above chance at 1.7 ms for upright faces ($t(31) = 5.56, p < .001$) and 2.6 ms for inverted faces ($t(31) = 3.76, p < .001$; this is roughly similar to the durations observed for location sensitivity, suggesting that awareness and detection sensitivity arose together; **Fig. 1D**, also see **Extended Data Fig. 1C** for metacognitive bias results). A FIE ($F_{(1, 31)} = 6.475, p = .016$) indicated better metacognitive sensitivity to upright than inverted faces. Similar to location sensitivity, emotion did not affect meta-d′ ($F < 1; \mathrm{BF}_{01} = 13.32$), suggesting that faces' emotional content is not prioritised for awareness. No interactions reached significance.

Overall, these findings indicate that processing emotion requires longer exposures than holistic face processing (a marker of face-specific processes), which requires longer exposures than intact-face detection.

Because of the many differences between peripheral and foveal vision[30], Experiment 2 examined whether this pattern of results would replicate for fixated stimuli. 32 new observers were shown brief displays of an intact and scrambled face, one after the other, for the same duration. Participants responded as in Experiment 1, but reported whether the intact face was first or second. Because of the better acuity of foveal vision, we set exposure durations to be slightly (0.2 ms) shorter than in Experiment 1. The pattern of results closely replicated that of Experiment 1; the differential effects arose in the same temporal sequence (**Fig. 1E-G**; also see **Extended Data Fig. 1D-F**, and **Supplementary Note 4** for full report on Experiment 2). To assess the possible contribution of afterimages to these observations, we ran two control experiments using reversed-contrast images (which resemble afterimages generated by the main experiments' stimuli), and found that afterimage processing could not account for the findings (see

Supplementary Note 5 for full report on these control experiments and **Supplementary Fig. 4-7**).

The findings so far show that intact-stimulus detection, holistic face processing, and emotion-specific processing emerge with around 2, 3-4, and 4-5 ms of visual exposure, respectively; upright faces gain access to awareness faster than inverted faces, whereas emotional expression does not affect either detection or awareness. Importantly, detection and awareness arise together: we find no evidence for unconscious processing, which would be indicated by above-chance sensitivity at shorter exposures for detection than for awareness. This evidence, however, is based on behavioural markers. Might the underlying neural activity unfold in ways that are not revealed by behavioural measures? And could such activity be found at shorter durations than those required for awareness, suggesting unconscious processing?

Neural markers of minimal required exposures

We used EEG to address these questions in Experiment 3: 32 new observers viewed similar displays to those of Experiment 1, but all faces were upright, and in addition to trial blocks with fearful and neutral expressions, we included blocks with happy and neutral expressions (see **Supplementary Note 6** for methodological description and **Supplementary Fig. 8-9**). To increase statistical power, we used just three durations: 1.7 ms (at which, according to Experiment 1, detection and awareness are above chance but holistic face processing and emotion-specific processing are absent), 4.4 ms (when holistic processing arises), and 6.2 ms (when emotion-specific processing is present).

Psychophysical sensitivity measures increased with duration, and were similar to the same durations' in Experiment 1 (see **Extended Data Fig. 2** for psychophysics results): Location sensitivity was already above chance at 1.7 ms, but expression had no effect on it at any duration; emotion identification sensitivity was above chance from 4.4 ms. Expression did not affect metacognitive sensitivity, which was already above chance at 1.7 ms, but significantly higher (and similar) at 4.4 and 6.2 ms.

We extracted several EEG event-related potentials (ERPs). We focus here on those related to emotion and awareness (for others, see **Supplementary Fig. 10**). Two ERP markers of emotion processing – the early posterior negativity (EPN[31]) and late positive potential (LPP[32]) – respond to intensity rather than valence, so fearful and happy expressions were collapsed and compared to neutral ones. For both markers, emotion interacted with duration *(EPN:*$(F_{(1.9,\,58.9)} = 8.675, p < .001)$*; LPP:*$(F_{(1.98,\,61.4)} = 9.8, p < .001)$, showing a significant difference between emotional and neutral faces only at 6.2 ms, the longest exposure (EPN:$t(87.6) = 4.009, p < .002$; LPP:$t(90.3) = 4.284, p < .001$), (**Fig. 2A-B**; see **Extended Data Fig. 3-5** to see additional topographies of these ERP markers). These ERP findings suggest, in line with our psychophysical results, that the minimal exposure required for emotion-specific processing is between 4.4 and 6.2 ms (see **Supplementary Note 7** for full report on Experiment 3).

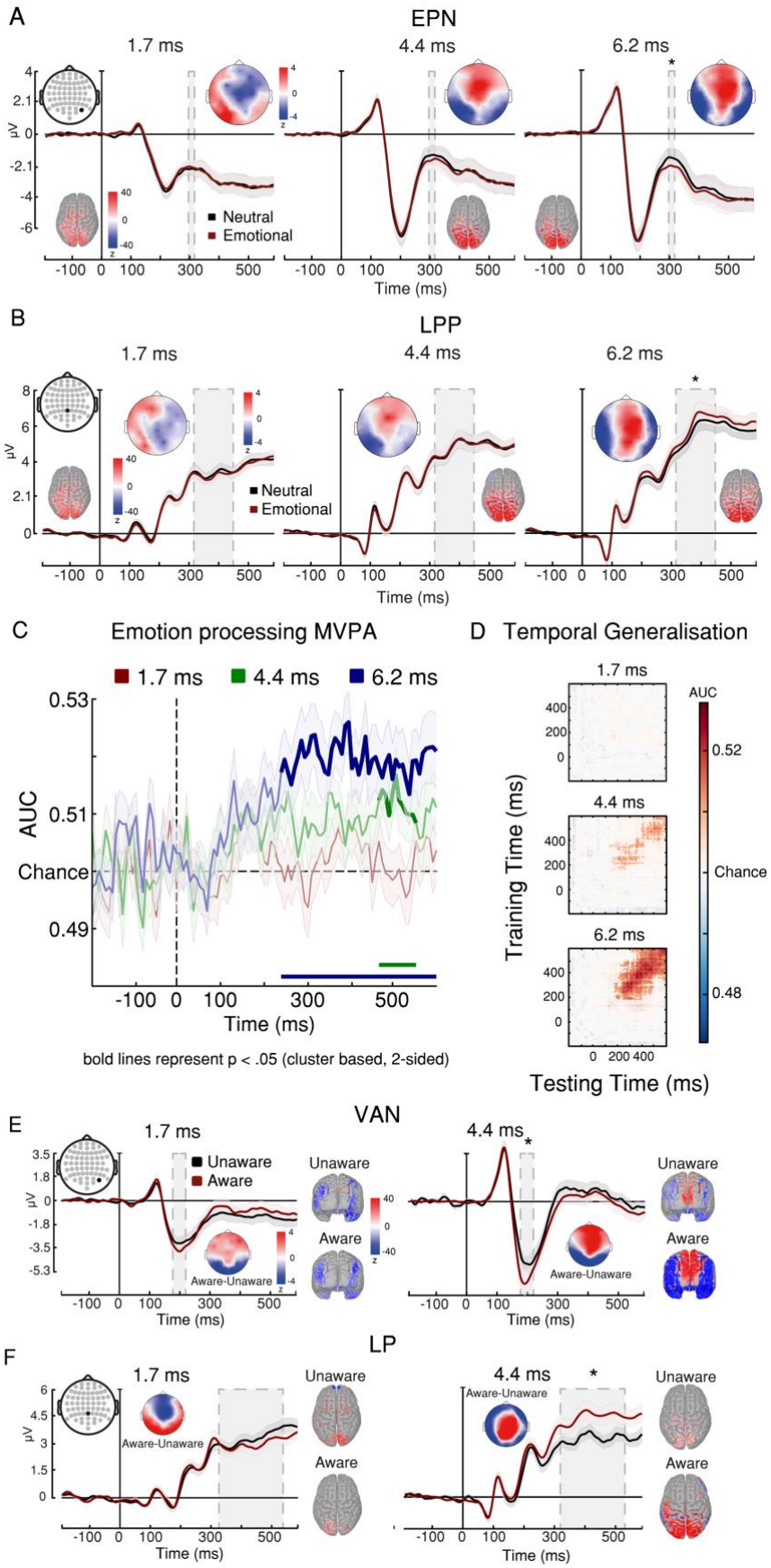

Fig. 2. Experiment 3: Neural measures of emotion processing and awareness. (A) and (B) EPN and LPP, ERP markers of emotion-processing, both discriminated between emotional and neutral

expressions only at the longest exposure. Topographic maps represent emotional – neutral voltage subtraction. Source estimation of the ERPs at their peaks are shown on cortical maps. (C) MVPA decoding of expression, showing limited success for 4.4 ms and robust classification for 6.2 ms exposure. (D) Temporal generalisation shows cortical signal stability across time. (E) and (F) VAN and LP, ERP markers of awareness, were modulated by awareness reports with 4.4 ms exposure. Time in all x-axes is from stimulus onset. Shaded contours: ±1 SEM. * p<0.05.

Because ERP analysis may not be sufficiently sensitive to neural patterns across electrodes, we examined emotion-related processing with multivariate pattern analysis (MVPA[33]). We trained a classifier to decode the 3 expressions, regardless of their location. The classifier had limited success at 4.4 ms, and robust success at 6.2 ms, demonstrating somewhat better sensitivity than ERPs but supporting the overall conclusion that emotion-specific processing requires at least 4 ms exposure (**Fig. 2C-D**; also see **Extended Data Fig. 6** for MVPA results of stimulus location).

To examine whether processing meaningful stimuli requires awareness, we divided trials into those with a subjective report of no awareness ("no experience" in the PAS) and those in which there was some level of awareness (all other PAS responses). Comparing the two categories, we extracted two ERP markers of awareness: the visual awareness negativity (VAN[34]) and the late positivity (LP[35,36]). As there were not enough no-awareness trials at 6.2 ms, this analysis was limited to durations of 1.7 and 4.4 ms (**Supplementary Fig. 11**). For both markers, there was an interaction between duration and awareness ($\text{VAN}: F_{(1,30)} = 10.062, p = .003; \text{LP}: F_{(1,30)} = 37.42, p < .001$); both ERPs distinguished between presence and absence of awareness significantly only at 4.4 ms (VAN: $t(45.4) = 5.21, p < .001; \text{LP}: t(55) = 5.861, p < .001$), (**Fig. 2E-F**); for VAN (but not LP), there was a numerical trend at 1.7 ms, in line with the small but above-chance meta-d' at this duration. Thus, neural findings show that the minimal exposure for awareness is equivalent to or precedes that for emotion processing.

Do neural systems require similar visual exposures to those found above in order to discriminate faces from non-face stimuli? In Experiment 4, 32 new observers viewed similar displays to those of Experiment 3, but each consisted of either a neutral-expression face or a highly-recognisable object (and their scrambled counterpart; Supplementary Note 8). We used four display durations (range 0.8 – 4.288 ms). Participants reported the location (left/right) and category (face/object) of the intact image, followed by a PAS rating.

Psychophysically, the minimal duration required for above-chance location and identification sensitivity was 1.4 ms (faces: $t(31) = 2.65, p = .013$; objects: $t(31) = 4.08, p < .001$; Identification: $t(31) = 2.09, p = .045$). Meta-d' was not affected by stimulus category ($F < 1$; $BF_{01} = 4.67$) and was above chance at 1.4 ms for both faces ($t(31) = 2.3, p = .028$) and objects ($t(31) = 3.64, p < .001$), (see **Extended Data Fig. 7** for psychophysics results).

We used an ERP marker of face processing, the N170 (which is greater for faces than objects[8,37]) to assess the minimal duration for specific face-related processing (for others, see **Supplementary Fig. 12**). The effects of duration and category on amplitude interacted ($F_{(2.5, 75.9)} = 6.398, p = .001$): the N170 successfully

discriminated faces from objects only at 4.288 ms ($t(114) = 3.467, p = .021$) (**Fig. 3**). These neural findings show a similar minimal exposure for face-specific processing – around 4 ms – as that needed for the FIE to arise in Experiment 1, converging on this duration as the minimal exposure required for engaging face-specific processes (see **Extended Data Fig. 8** to see additional topographies of the N170; see **Extended Data Fig. 9** for VAN results and **Extended Data Fig. 10** for LP results; and see **Supplementary Note 8** for full report on Experiment 4).

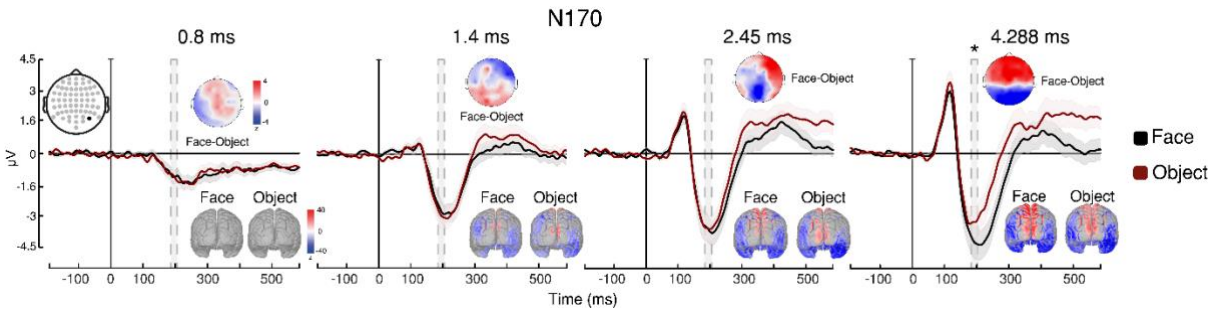

Fig. 3. Experiment 4: Neural measures of face vs. object processing. The N170, an ERP marker of face processing, discriminated between faces and objects only at the longest exposure. Topographic maps represent face – object voltage subtraction. Source estimation of the ERPs at their peaks are shown on cortical maps. Time in all x-axes is from stimulus onset. Shaded contours: ±1 SEM. * p<0.05.

DISCUSSION

Overall, psychophysical and neural measures converge to clarify the sequence of minimal exposures needed for face processing to unfold: above-chance stimulus detection requires 1-2 ms, face-specific processes require 3-4 ms, and emotion-specific processes require at least 4 ms. Awareness arises hand-in-hand with detection, increasing with exposure duration but evident with as little as 1.4 ms. Face orientation affects the minimal exposures required for detection and awareness, indicating prioritisation of holistic processing. Emotion processing, however, does not affect minimal exposures, and is only evident at longer durations than those at which face detection is reliable and face-specific processes are engaged. No sensitivity measures rise above chance at shorter exposures than required for awareness.

These findings set upper bounds on the minimal exposures required for object detection, face-specific processing, emotion processing, and visual awareness: although shorter durations may yet be found for higher-luminance or more distinctive stimuli, longer minima are ruled out. Crucially, our findings demonstrate that seeing a face as an intact object is not sufficient for engaging face-specific processing, and that the presence of face-specific processing does not guarantee emotion processing. This contradicts suggestions that perceiving an object's location entails perceiving its full nature[38]; furthermore, it is inconsistent with the proposal that awareness of all stimulus attributes arises simultaneously (e.g., through 'ignition'[9,10]). Our measure of awareness only assessed subjective

experience in general, rather than awareness of specific attributes; but the presence of above-chance metacognitive sensitivity at shorter durations than those required for holistic or emotion processing suggests that observers have some awareness of the intact stimulus before perceiving those attributes, supporting the possibility that awareness of different aspects of the same stimulus may require different amounts of information.

The absence of any evidence for subliminal perception reveals awareness' primacy: Although masking studies have provided evidence for unconscious processing[21,39–41], our findings suggest that when not actively disrupted by masks, perceptual processing and awareness arise together. This raises the possibility that awareness may be a condition for certain types of processing.

Great efforts have been made to characterise the visual processing hierarchy, mostly by describing the anatomical arrangement of specialised processing regions[42,43]. The present study offers a complementary approach, enabling elucidation of the functional dynamics of this hierarchy – how well the system is attuned to different stimulus attributes – by assessing the minimal exposure required for the relevant information to propagate through the system and reach dedicated processing. The face stimuli used here provide a proof of concept for the utility of this approach, which may yield further valuable insights by application to both lower-level features and higher semantic categories.

METHODS

Psychophysics

We used Signal Detection Theoretic (SDT) measures to assess how perceptual sensitivity, metacognitive sensitivity, and decision criteria changed across display durations. To determine each participant's bias-independent sensitivity to face location (left or right; henceforth referred to as location d') for each combination of duration, face orientation, and emotional expression, we employed the calculation for two-alternative forced choice (2AFC) tasks for perceptual sensitivity and criterion (type-1 SDT[44]), $d'_{location} = \left(\frac{1}{\sqrt{2}}\right)(Z(Hit_{location}) - Z(FA_{location}))$, where Z(Hit) stands for the Z score associated with the probability of a Hit (defined as a trial in which a face was displayed on the right and reported on the right), and Z(FA) for that associated with the probability of a false alarm (a trial in which a face was displayed on the left but reported as being on the right). To estimate each participant's bias to respond left or right (henceforth referred to as response bias) during face location, we employed the calculation $C_{location} = -\left(\frac{1}{2}\right)(Z(Hit_{location}) + Z(FA_{location}))$. Positive and negative values for this measure indicate a bias toward responding "left" and "right", respectively; however, as these may cancel out across participants, we converted the results to absolute values as a measure of response bias quantity. To determine how sensitive each participant's awareness judgment (PAS ratings) was to their location sensitivity performance (metacognitive sensitivity; henceforth referred to as meta-d') and the bias in such judgments (metacognitive bias; henceforth referred to as meta-bias), we employed the maximum likelihood estimation procedure

developed by Maniscalco and Lau[45-47] (http://www.columbia.edu/~bsm2105/type2sdt/).
To determine emotional identification sensitivity (to fearful expressions versus neutral expressions; henceforth referred to as identification d′), we used the calculation of d′ for Yes-No detection tasks, $d'_{identification} = Z(Hit_{identification}) - Z(FA_{identification})$, where a hit was defined as correctly reporting a fearful expression and FA was defined as incorrectly reporting a fearful expression. To estimate each participant's identification criterion during emotion expression identification, we employed the calculation $C_{identification} = -\left(\frac{1}{2}\right)(Z(Hit_{identification}) + Z(FA_{identification}))$. These measures were calculated by-condition for each participant and analysed using analysis of variance (ANOVA). Greenhouse-Geisser adjusted degrees of freedom were used when Mauchly's test indicated a violation of the sphericity assumption.

Electroencephalography

EEG data were recorded and digitised at a sampling rate of 512 Hz using a 64-channel Biosemi system with an elastic cap, in which electrodes were integrated at sites conforming to the 10-20 system. All impedance values were kept below 50 kΩ. Scalp electrodes were referenced to Cz. The continuous EEG data was resampled to 256 Hz, then filtered leaving frequencies between 0.3 and 40 Hz, and finally epoched from 200 ms before to 600 ms after stimulus onset. An independent-component analysis (ICA) was run on the epoched EEG signal. Components attributed to eye blinks, ocular movements, heartbeat, and channel noise were taken out. Trials with voltage exceeding 150 mV were excluded from further analysis. On average, 1.8% of trials were removed. The EEG signal was then re-referenced to the average across all electrodes. Waveforms were then averaged for all electrodes. By eye inspection on canonical sites, we determined the following electrodes for each event-related potential (ERP) component of interest: P1 (Oz), left N170 (PO7), right N170 (PO8), left VAN (PO7), right VAN (PO8), VPP (FCz), left EPN (P7), right EPN (P8), LPP (Pz), and LP (Pz). Because emotion processing-related components (EPN and LPP) mainly respond to emotional intensity rather than valence[48,49], and because we wanted to preserve a balanced number of trials between conditions, we collapsed all components across trials, separately for emotional trials (fearful and happy expressions together) and neutral trials (neutral expressions) in Experiment 3. ERP components were collapsed across trials from the same stimulus condition regardless of behavioural performance in the task, except for our pre-registered analyses of VAN and LP (https://aspredicted.org/53sv5.pdf). These two components were collapsed across two groups of trials according to the trials' PAS ratings: awareness-present trials (PAS ratings of "vague impression", "almost clear experience", or "clear experience") and awareness-absent trials (PAS rating of "no experience"). To investigate changes in ERP components, mean amplitudes were computed within the following time windows: 105-135 ms (P1), 170-200 ms (N170 and VPP), 295-325 ms (EPN), 310-430 ms (LPP), 185-215 ms (VAN), and 320-520 ms (LP). These time windows were determined by eye inspection on the grand average plots, in specific time windows informed by previous studies, and did not involve exploratory statistical testing, as a way to reduce familywise error[50,51].
In Experiment 4, EEG recording and pre-processing was performed with two differences: first, based on eye inspection of canonical sites, we selected slightly

different time windows for the following ERP components: P1 (105-135), N170/VPP (175–205 ms), VAN (200–230 ms), and LP (300–585 ms). Second, mean amplitudes were not computed for EPN and LPP.

Event-related potential analysis

In Experiment 3, ERP analysis was performed on mean amplitude values of each ERP component at the specific electrodes and time windows stated above. We reconstructed each ERP's cortical source using Brainstorm (Tadel et al.[52], version released in October 2019). To estimate the cortical source of an ERP component, we need to model the electromagnetic properties of the head and of the sensor array (forward model), and then estimate the brain sources that produced the EEG signal of interest (inverse model). The forward model was calculated using the OpenMEEG Boundary Element Method[53] on the cortical surface of a template MNI brain (ICBM152) with 1 mm resolution. The inverse model was constrained using weighted minimum-norm estimation[54] (wMNE) to measure source activation in picoampere-meters. wMNE looks for a distribution of sources with the minimum current that can account for the EEG data. We corrected grand-averaged activation values by subtracting the mean of the baseline period (-200 to 0 ms before stimulus onset) and spatially smoothed with a 5-mm kernel. This procedure was applied separately for each ERP component.

Multivariate pattern analysis

To complement ERP analysis, an MVPA on the raw EEG data was applied using the ADAM toolbox[55]. To achieve this, we used a classification algorithm based on linear discriminant analysis (LDA). To keep a balanced number of trials between conditions[56], we randomly selected and discarded trials when necessary ("undersampling"[55]). To measure classification performance, we calculated the area under the curve accuracy metric (AUC) of the receiver operating characteristic (ROC), a measure derived from SDT insensitive to classifier bias[57,58]. Finding above-chance classification performance indicates that there is information contained in the EEG data that was decoded based on the experimental conditions of interest.
Four independent backward decoding algorithms (automated classifiers), following a 10-fold cross-validation approach (including all electrodes and time points), were applied using: (1) intact-face location as class; and (2) emotional expressions as class, i.e., fearful, happy, and neutral expressions (Experiment 3). AUC scores were tested per time point with double-sided t-tests cluster-corrected for multiple comparisons[59] with a standard cut-off p-value of .05 (1000 iterations).

Statistical information

Both frequentist (repeated-measures ANOVA and two-tailed t-tests) and Bayesian (Bayes factors) statistical analyses were performed using Jamovi[60] and corroborated using JASP[61] and R. When an ANOVA indicated a significant interaction, we ran post hoc Bonferroni-corrected pairwise comparisons to look for significant effects. Post hoc pairwise comparisons in these statistical packages use estimated marginal means based on the variance of the ANOVA model. For Bayes factor analysis, we defined the null hypothesis as no difference between conditions by using a standard Cauchy distribution centred on zero with rate of 0.707.

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Author contribution
R.C.L., H.R., and D.C. conceived the study. R.C.L., H.R., A.C., and D.C. conceptualised the study. R.C.L., H.R., A.C., and D.C., acquired funding, R.C.L, H.R., and D.C. designed the experiments. R.C.L. programmed the experiments, collected the data, and analysed the data. A.C-J, H.R., A.C., and D.C. supervised the data analysis. R.C.L. and D.C. wrote the manuscript with input from all authors.

Competing interests
The authors declare no competing interests.

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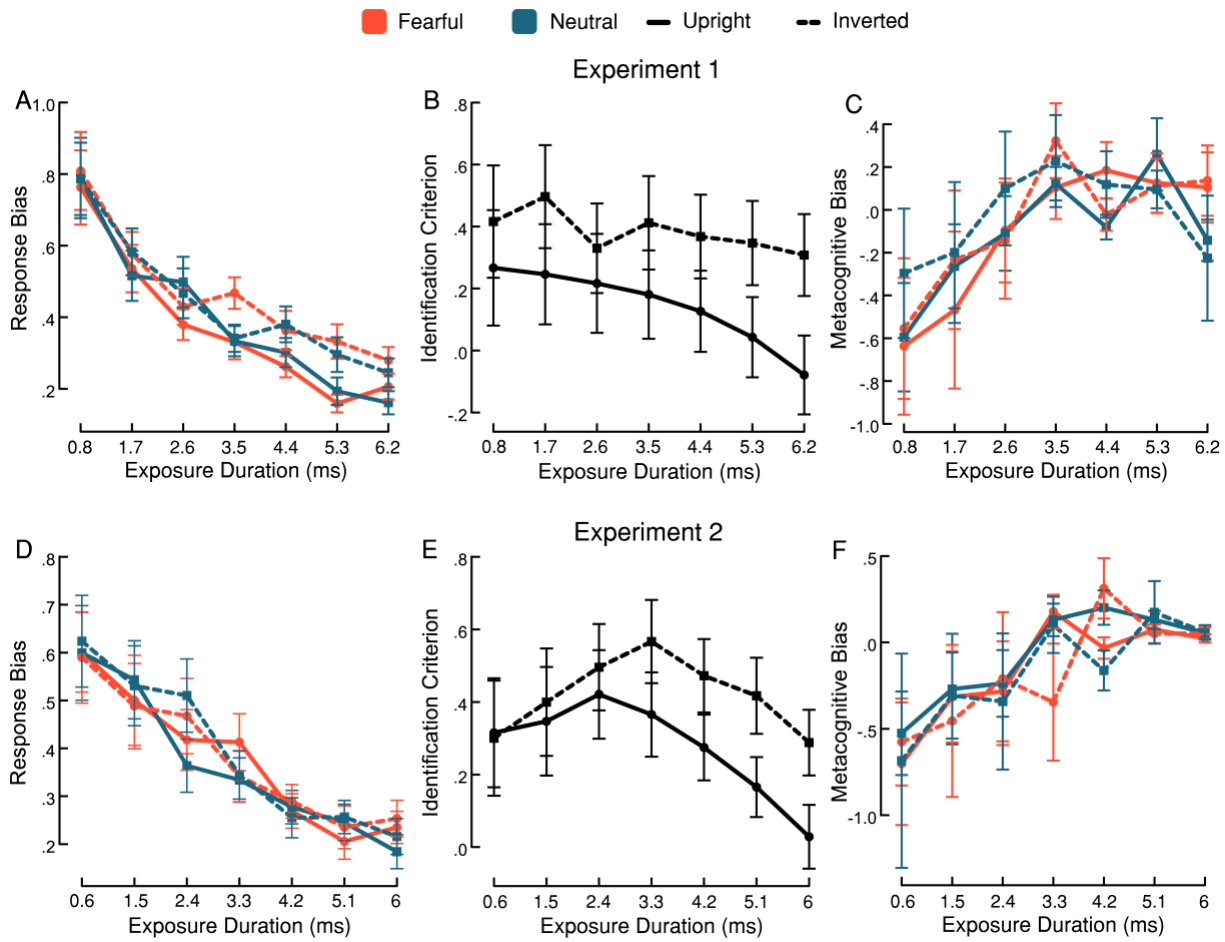
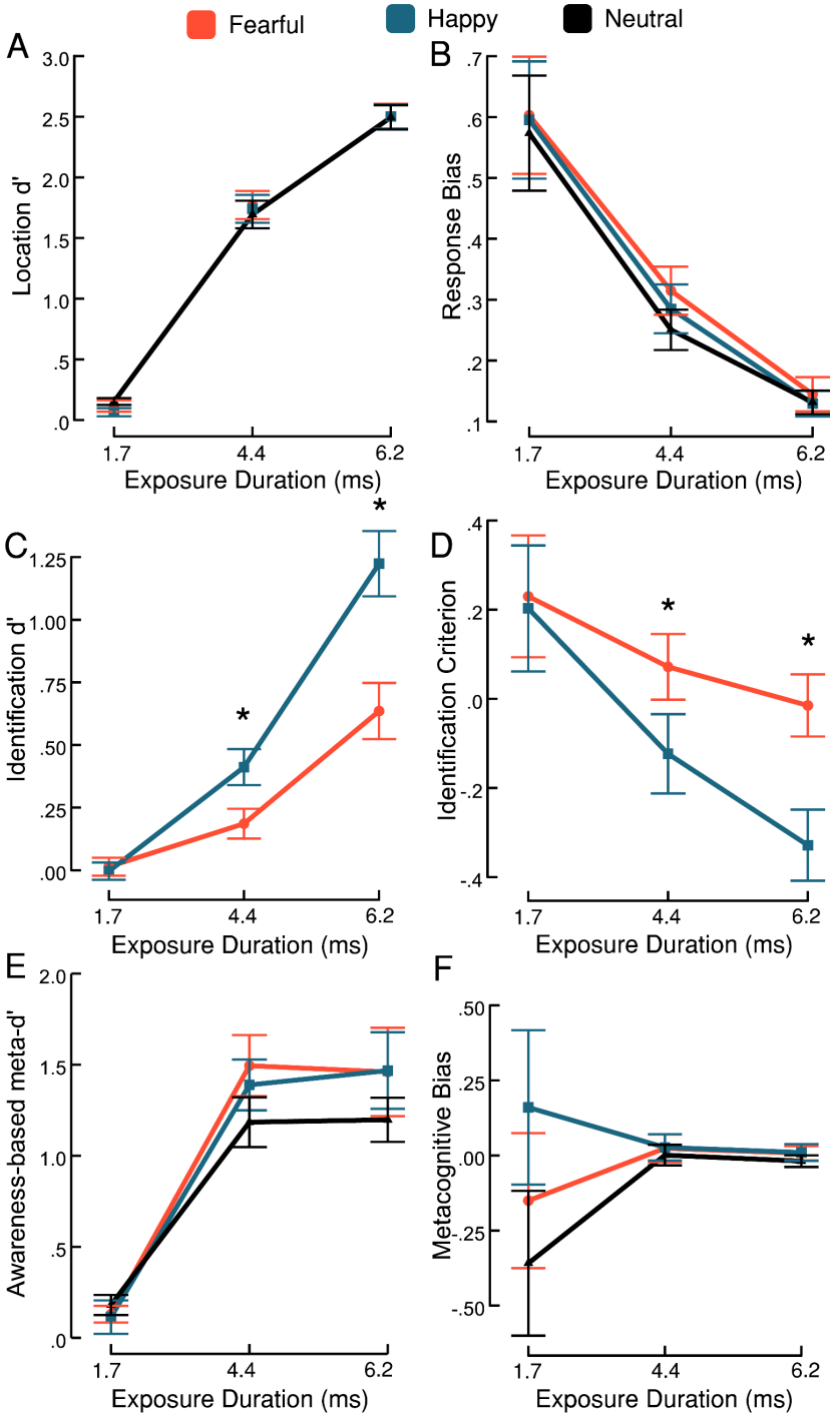
Data availability
Processed data are available at https://osf.io/d2kvc/.

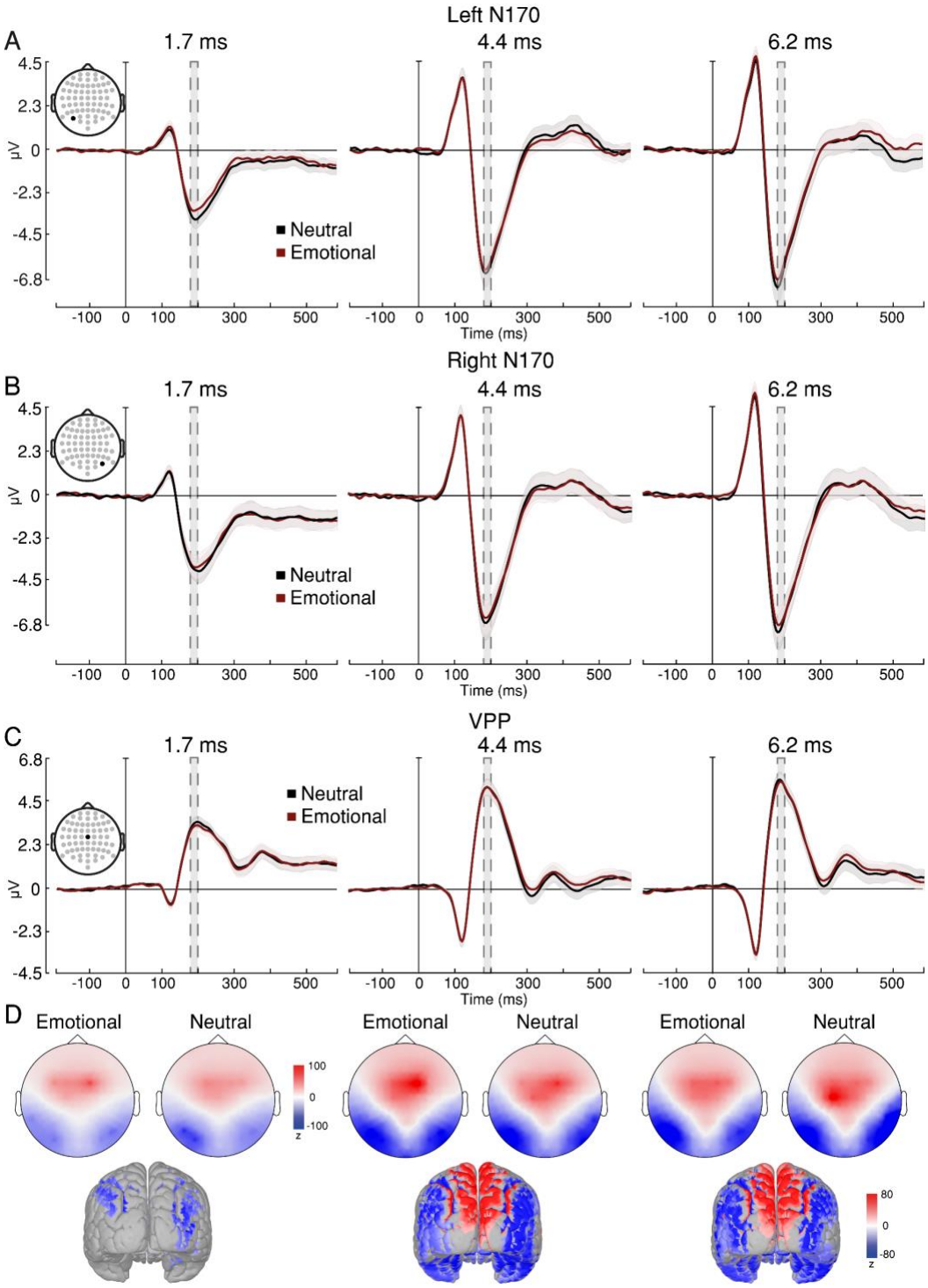
EXTENDED DATA FIGURES



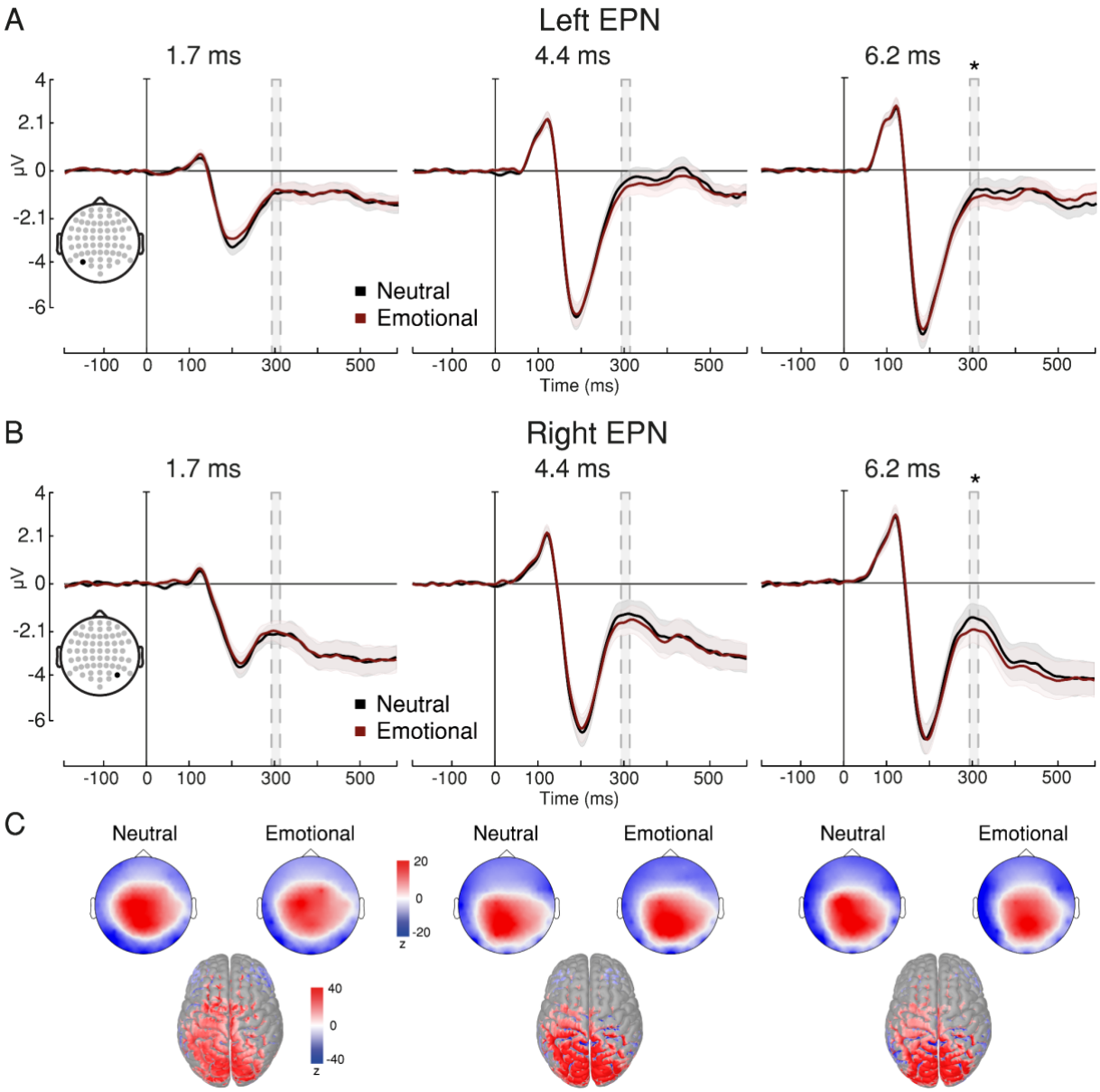
Extended Data Fig. 1. (A-C) Additional results of Experiment 1. (A) Absolute-value response bias scores for reporting location (bias toward either left or right). The amount of response bias decreased as exposure duration increased, with slightly (but significantly) greater bias for inverted faces over upright faces. However, there was no statistically significant difference between fearful and neutral expressions (B) Criterion scores for reporting expression. Although we did not find main effects of exposure duration and face orientation, we did find a significant interaction between these two factors. However, post hoc comparisons did not reveal significant differences. (C) Metacognitive bias scores for reporting subjective awareness. Lower scores denote a more liberal bias to report higher confidence. Meta-bias increased as exposure duration increased, suggesting that participants were more willing to exhibit lower confidence than in shorter exposure durations.
(D-F) Additional results of the Experiment 2. (D) Absolute-value response bias scores for reporting presentation order of the intact face (bias toward reporting either first or second). The amount of bias decreased as exposure duration increased, but there was no difference in amount of response bias between expressions and orientations. (E) Criterion scores for reporting expression. Upright faces exhibit a significantly more liberal criterion (lower values) than inverted faces during expression identification. (F) Metacognitive bias scores for reporting subjective awareness. Lower scores denote a more liberal bias to report higher confidence. Meta-bias increased as exposure duration increased, suggesting that participants were more willing to exhibit lower confidence than in shorter exposure durations. Error bars represent SEM.



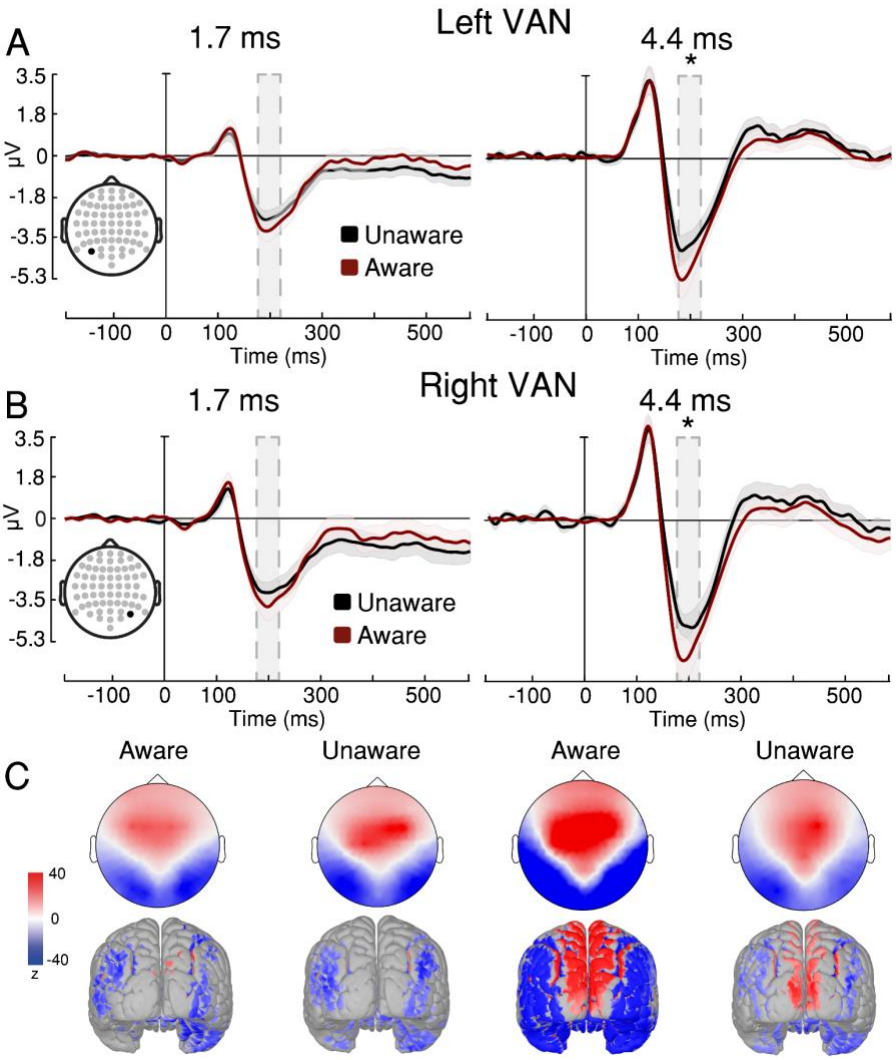
Extended Data Fig. 2. Full behavioural results of Experiment 3. (A) Location sensitivity. Location d′ increased with increasing exposure duration. There was no effect of emotional expression. (B) Absolute-value response bias scores for reporting location (bias toward either left or right). The amount of bias decreased as exposure duration increased, but there was no difference in amount of response bias between expressions. (C) Identification sensitivity for expression. Identification d′ increases with increasing exposure duration. A significant advantage in expression identification for happy expressions over fearful expressions arises by 4.4 ms of exposure. (D) Criterion scores for reporting expression. Criterion becomes more liberal with increasing exposure duration. A more liberal criterion for happy expressions over fearful expressions arises by 4.4 ms of exposure. (E) Awareness-based metacognitive sensitivity. Meta-d′ increased with exposure duration but was unaffected by expression. (F) Metacognitive bias scores for reporting subjective awareness. Metacognitive bias was unaffected by exposure duration and expression. Asterisks index statistically significant differences between fearful and happy expressions. Error bars represent SEM.



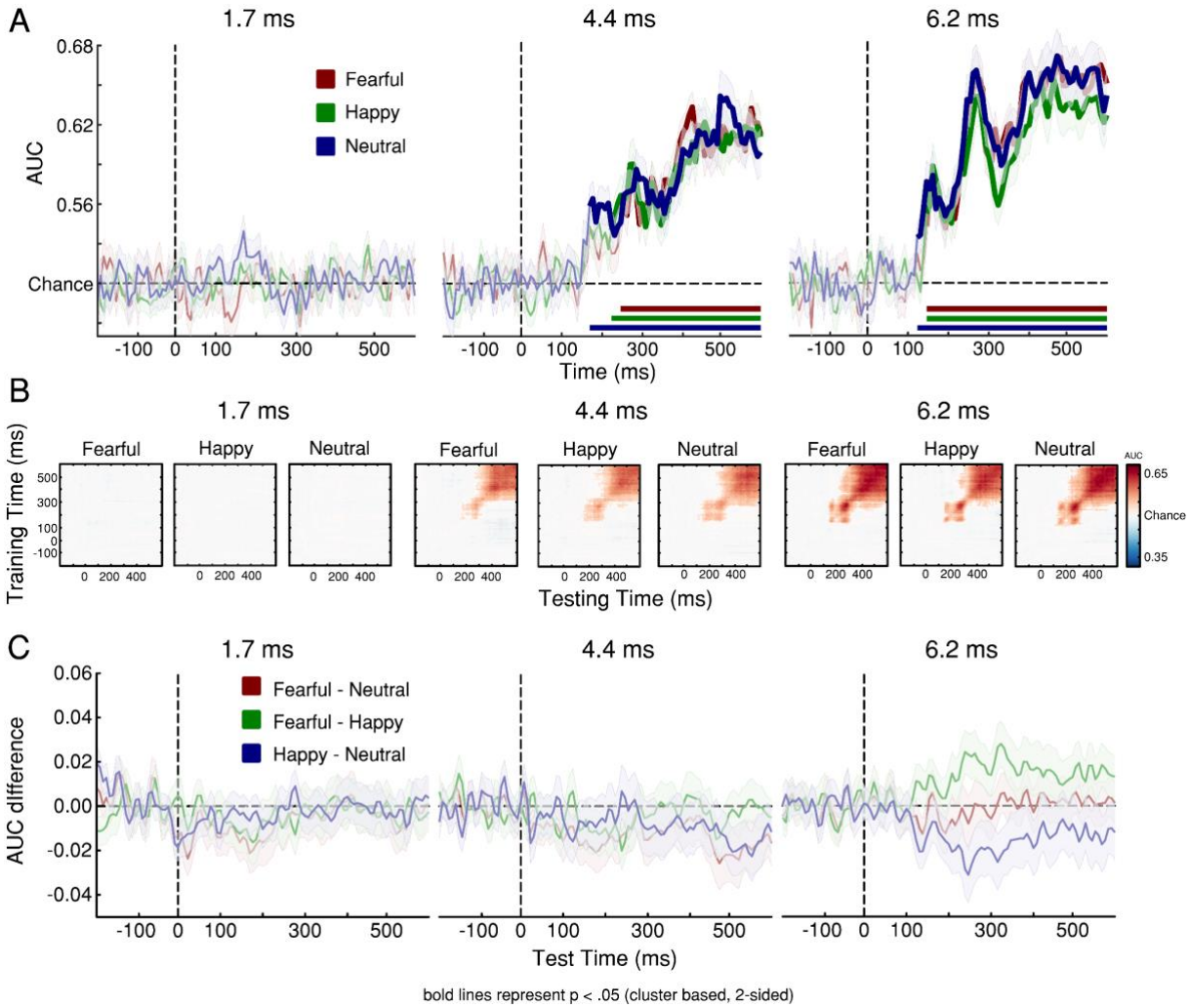
Extended Data Fig. 3. Face processing indexed by N170/VPP. (A) Left N170, (B) right N170, and (C) VPP response to emotional and neutral expressions across exposure durations. N170/VPP peak with averaged time window highlighted in grey (170–200 ms). (d) Topographical distributions of N170/VPP for each condition at the relevant time window (z-scale: from -100 to 100). Source estimation of N170/VPP visually identified on cortical maps (z-scale: from -80 to 80. Shaded areas represent SEM.



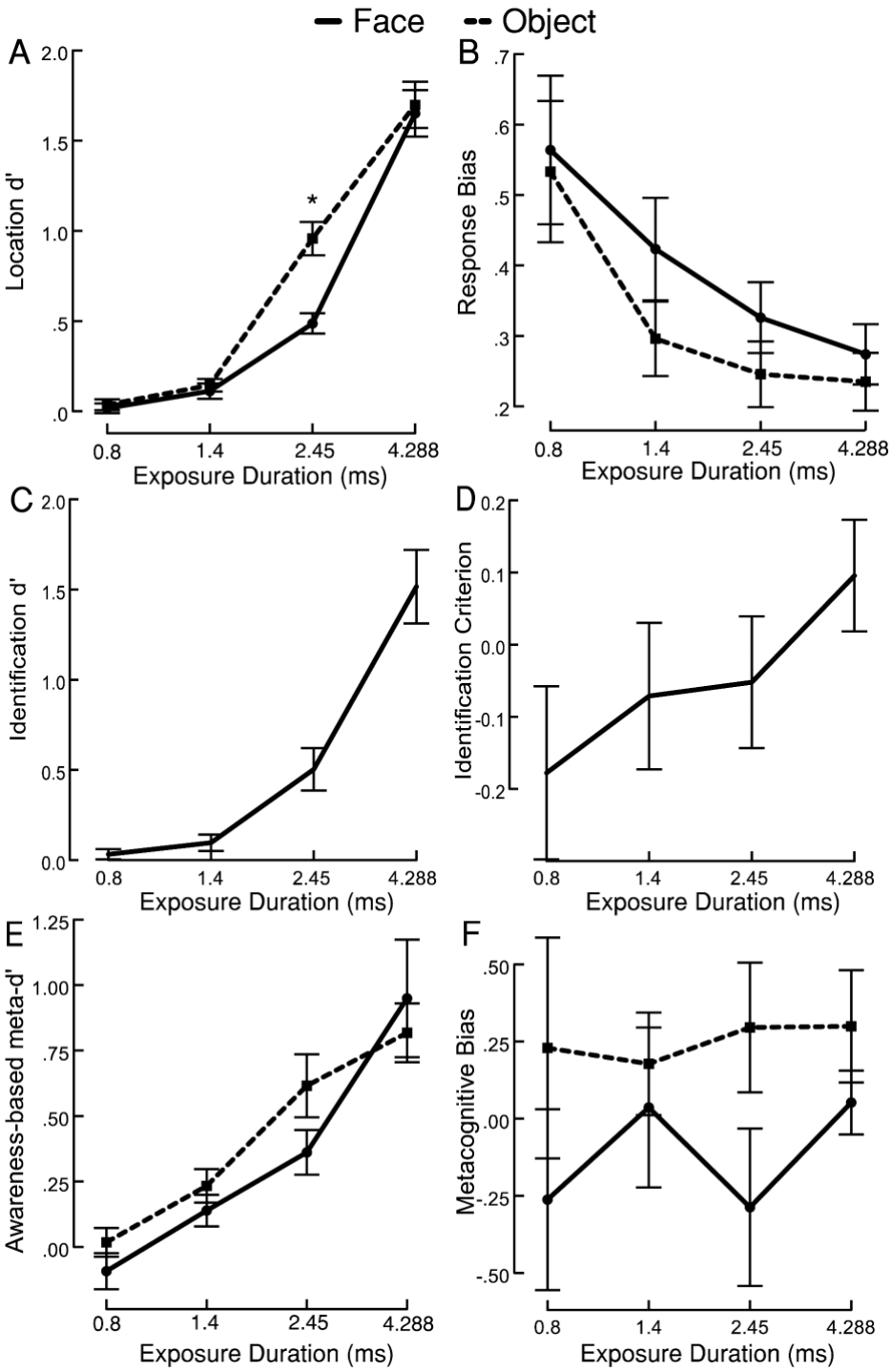
Extended Data Fig. 4. Early emotion processing indexed by EPN. (A) Left EPN and (B) right EPN response to emotional and neutral expressions across exposure durations. EPN peak with averaged time window highlighted in grey (295–325 ms). Emotional expressions had significantly more negative voltage than neutral expressions at 6.2 ms of exposure. (C) Topographical distributions of EPN for each condition at the relevant time window (z-scale: from -20 to 20). Source estimation of EPN visually identified on cortical maps (z-scale: from -40 to 40). Asterisks indicate statistically significant differences between conditions. Shaded areas represent SEM.



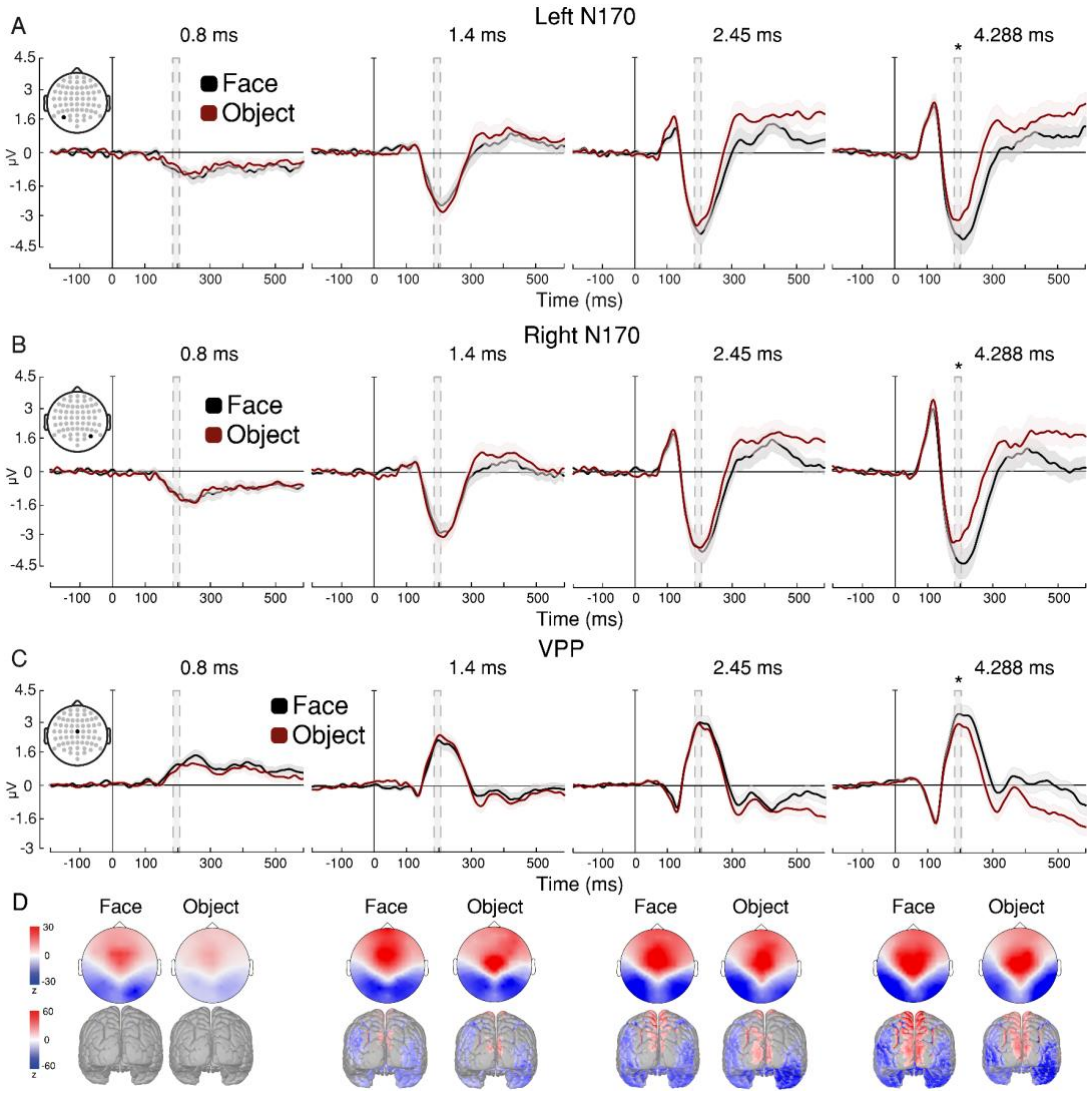
Extended Data Fig. 5. Visual awareness indexed by VAN. (A) Left and (B) right VAN response across awareness ratings and exposure durations. Emotional expressions are collapsed together. Averaged time window highlighted in grey (185-215 ms). Awareness-present trials had significantly more negative voltage than awareness-absent trials at 4.4 ms of exposure. (C) Topographic maps of VAN (z-scale: from -40 to 40). Source estimations of the ERP at its voltage peak are visually identified on cortical maps (z-scale: from -40 to 40). Asterisks indicate significant differences between aware and unaware trials. Shaded areas represent SEM.



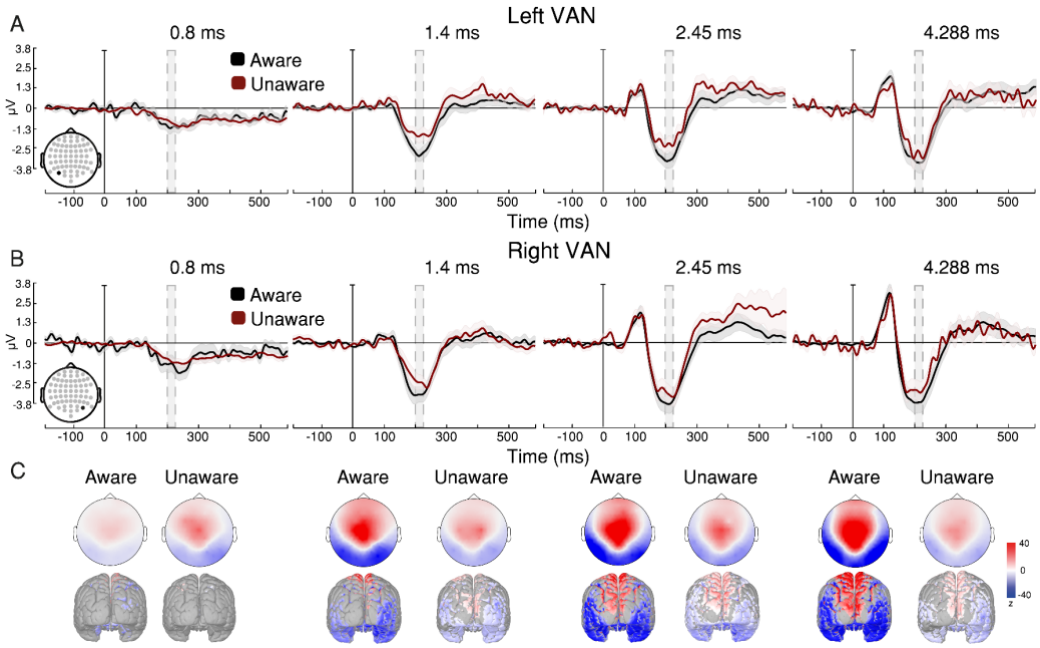
Extended Data Fig. 6. MVPA of intact-face location. (A) Classifier AUC scores decoded significantly above chance intact face location only at 4.4 and 6.2 ms of exposure. (B) Temporal generalisation analysis. The Y-axis depicts training time points, and the X-axis depicts testing time points, relative to stimulus presentation (time zero). AUC scores revealed broad temporal generalisation of the decoded multivariate patterns at 4.4 and 6.2 ms of exposure. (C) AUC difference between pairs of expressions. No paired comparison revealed significant clusters, suggesting that no emotional expression enjoyed above-chance classification at any exposure duration. Solid bold lines at the bottom of the charts represent significant clusters ($p < .05$, cluster-corrected) and shaded contours represent SEM.



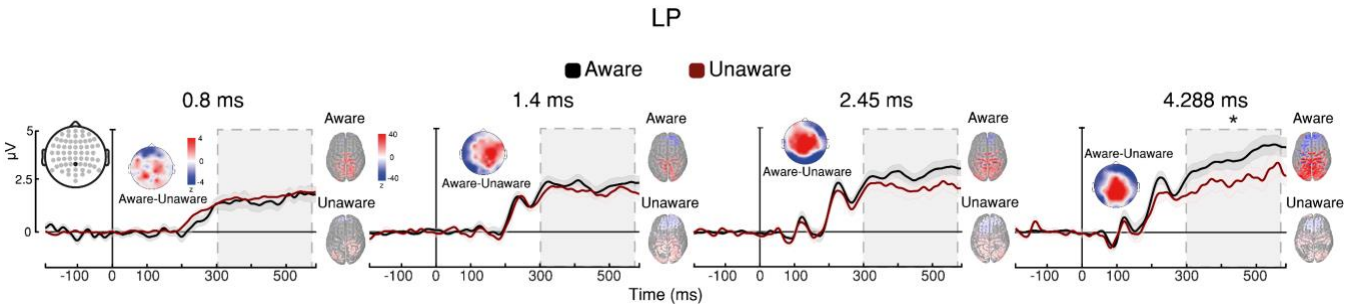
Extended Data Fig. 7. Full behavioural results of Experiment 4. (A) Location sensitivity. Location d' increased with increasing exposure duration. A significant advantage for objects over faces was found at 2.45 ms of exposure. (B) Absolute-value location response bias scores for reporting location (bias toward either left or right). The amount of bias decreased as exposure duration increased, with greater bias for faces than objects. (C) Identification sensitivity for stimulus category. Participants' ability to discriminate faces and objects increased with exposure duration. (D) Criterion scores for reporting stimulus category. Lower criterion indicates greater bias to reporting a face. Criterion does not significantly change with increasing exposure duration. (E) Awareness-based metacognitive sensitivity. Meta-d' increased with exposure duration but was unaffected by stimulus category. (F) Metacognitive bias scores for reporting subjective awareness. Metacognitive bias was unaffected by exposure duration and stimulus category. Asterisks index statistically significant differences between faces and objects. Error bars represent SEM.



Extended Data Fig. 8. Face processing indexed by N170/VPP. (A) Left N170, (B) right N170, and (C) VPP response to face and object stimuli across exposure durations. N170/VPP peak with averaged time window highlighted in grey (175–205 ms). (D) Topographical distributions of N170/VPP for each condition at the relevant time window (z-scale: from -30 to 30) and source estimations visually identified on cortical maps (z-scale: from -60 to 60). Shaded areas represent SEM.



Extended Data Fig. 9. Visual awareness indexed by VAN. (A) Left and (B) right VAN response across awareness ratings and exposure durations. Stimulus categories are collapsed together. Averaged time window highlighted in grey (200-230 ms). (C) Topographic maps of VAN (z-scale: from -4 to 4). Source estimations of the ERP at its voltage peak are visually identified on cortical maps (z-scale: from -40 to 40). Shaded areas represent SEM.



Extended Data Fig. 10. Visual awareness indexed by LP. LP response across awareness ratings and exposure durations. Stimulus categories are collapsed together. Averaged time window highlighted in grey (300-585 ms). Topographic maps of LP (z-scale: from -4 to 4). Source estimations of the ERP at its voltage peak are visually identified on cortical maps (z-scale: from -40 to 40). Shaded areas represent SEM.