Minimal exposures reveal visual processing priorities

Measuring the minimal display durations needed for perception and awareness shows the attributes to which vision is attuned.

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Abstract

Human vision parses brief displays remarkably well, but the minimal stimulation required to extract meaning from visual stimuli is unknown. Finding the minimal exposures needed for perception and awareness of various attributes can elucidate vision's priorities. We used a novel display enabling extremely brief presentations to establish the minimal durations required for processing a highly-meaningful category: human faces. Neural and psychophysical findings converge to reveal a sequence of minimal exposures required for object-level detection (1-2 ms), face-specific processing (3-4 ms), and emotion-specific processing (4-5 ms). Face orientation affected minimal exposure, but emotional expression did not. Awareness emerged with detection; we found no evidence of subliminal processing. These findings uncover the information to which the visual system is attuned, demonstrating which attributes can modulate this tuning.

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. This requirement cannot be characterised in terms of stimulus energy, because the system may be differentially sensitive to attributes that are distinguished by stimulus configuration rather than physical amplitude (*3–5*). Observers are able to extract large amounts of information from brief displays, and certain types of information are perceived more readily than others (*4–8*), suggesting that visual pathways are calibrated – perhaps by the top-down influence of pre-existing internal models (*9*) – to prioritise certain stimulus properties for processing. The more attuned the system is to a visual feature, the less exposure to this feature should be required to process it. Therefore, an understanding of the minimal exposure required for processing various aspects of a visual stimulus can shed light on the system's priorities.

Furthermore, minimal exposures can capture the functional and neural distinction between subliminal and supraliminal processing by measuring the durations required for explicit detection and comparing them to the durations required for stimulus-evoked neural activity and behavioural measures of awareness. 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' (*10*, *11*), 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 (*12*) and predictive (*13*) processing, and recent modifications of the GNWT (*14*)), 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, hardware limitations have precluded the measurement of such minima, 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 stimulus-mask interactions, making it impossible to determine the minimal exposure required for perceptual processing of single stimuli.

We used a newly-developed LCD tachistoscope that enables extremely

brief visual presentations with microsecond-level precision (Fig. S1), (*15*). 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 (*16–18*), and for emotional over neutral faces (*19*, *20*). (Although the latter claim, in particular, has been challenged (*21*)). If so, processing – and possibly awareness – of upright and emotional faces should require shorter minimal exposures than inverted and neutral faces, respectively.

We first investigated these hypotheses psychophysically (Materials and Methods): 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 (Figs. S2-S3). 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).

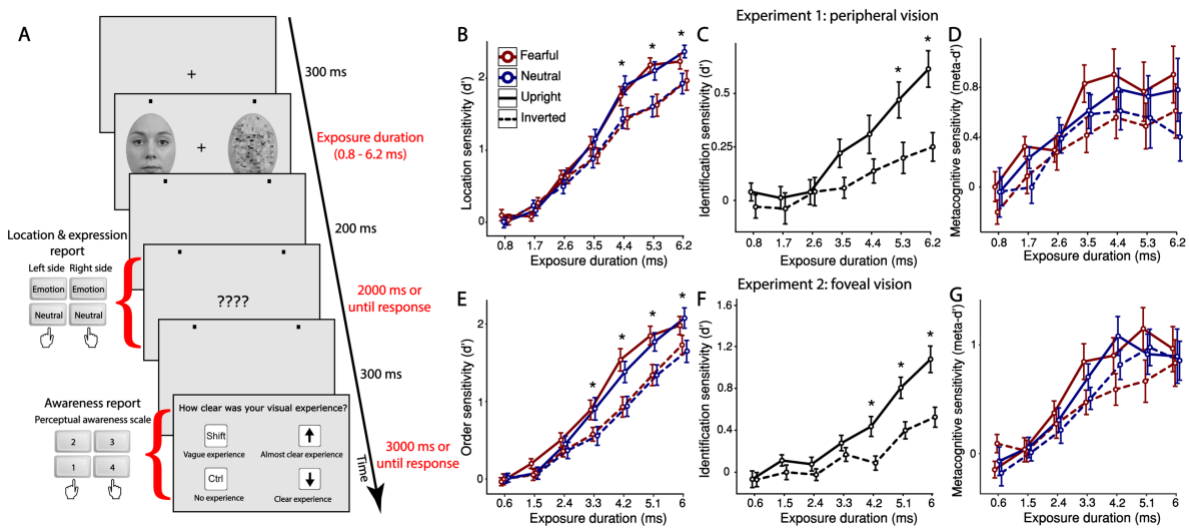

Fig. 1. Schematic trial procedure and psychophysical measures of location, emotion identification, and metacognitive sensitivity. (A) Experiment 1: An intact and scrambled face were presented for one of seven possible exposure durations (range 0.8 – 6.2 ms). Participants pressed one key to report both 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 ($F_{(1.99, 61.97)} = 215.135, p < .001$) (supplementary text; Fig. S8). 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 (*16–18*). 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 (Fig. 1B).

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). 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 (*22*)) 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 (*23*) – the correspondence between participants' location performance and PAS reports – as a proxy measure of awareness (*24*). 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). 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 (*25*), 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 (Fig. S4). 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; Fig. S9). 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 (supplementary text, section 3).

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?

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 (Figs. S5). 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 (Fig. S14): 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 Figs. S15-S19). Two ERP markers of emotion processing – the early posterior negativity (EPN, (*26*)) and late positive

potential (LPP, (*27*)) – respond to intensity rather than valence, so fearful and happy expressions were collapsed and compared to neutral ones (Fig. S6). 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**). 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.

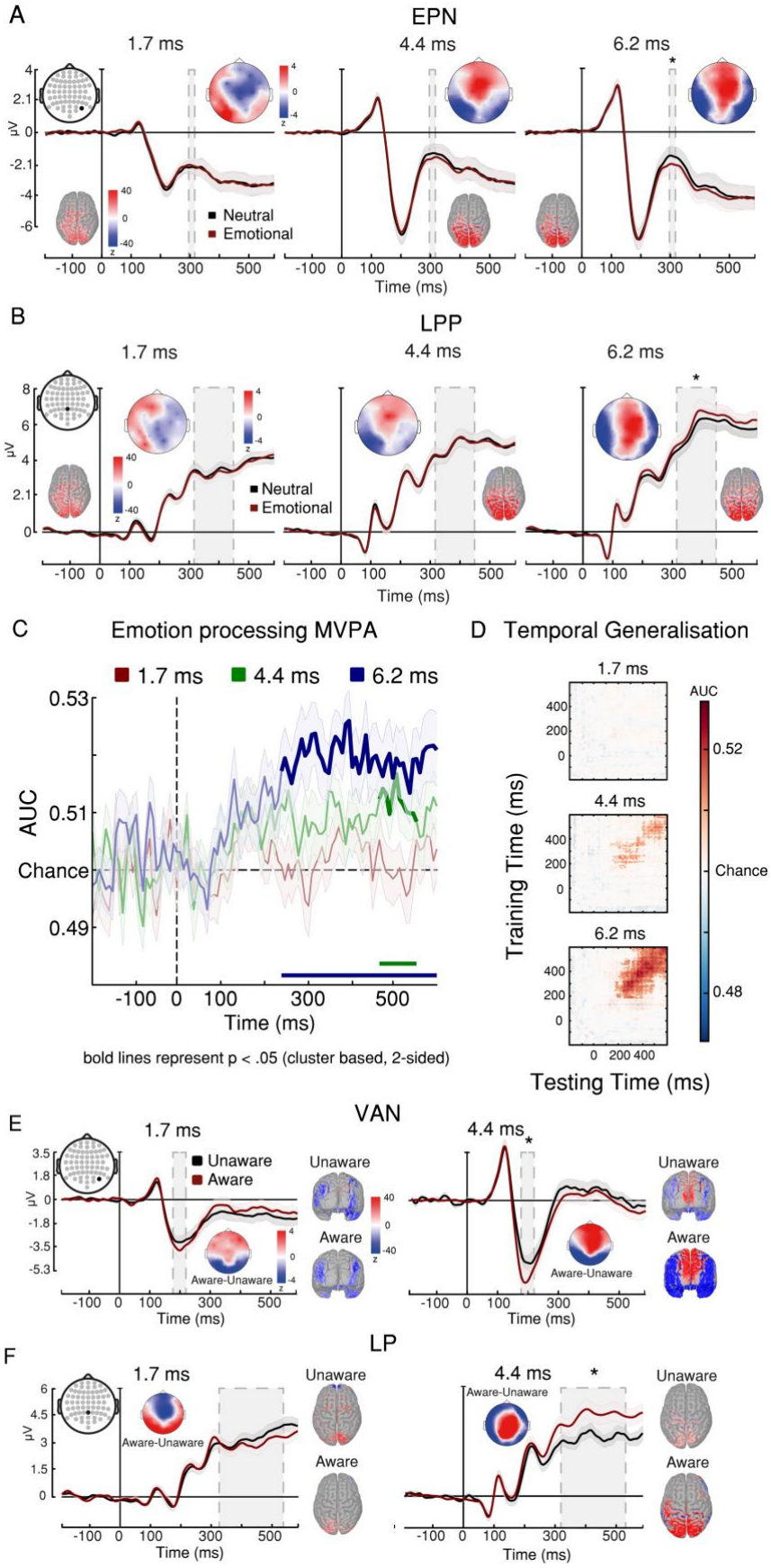

Fig. 2. Experiment 3: Neural measures of emotion processing and awareness. (A) and (B) EPN and LPP, ERP markers of emotion-processing, both discriminated between emotional and neutral

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; (*28*)). 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 Fig. S20).

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; (*29*)) and the late positivity (LP; (*30*, *31*)). 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 (Fig. S18). For both markers, there was an interaction between duration and awareness (VAN: $F_{(1, 30)} = 10.062, p = .003$; LP: $F_{(1, 30)} = 37.42, p < .001$); both ERPs distinguished between presence and absence of awareness significantly only at 4.4 ms (VAN: $t(45.4) = 5.21, p < .001$; 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; Fig. S7). 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 ($t(31) = 3.64, p < .001$) (supplementary text; Fig. S21).

We used an ERP marker of face processing, the N170 (which is greater for faces than objects; (*3*, *32*)) to assess

the minimal duration for specific face-related processing. 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 (for other markers, see Figs. S22-S25).

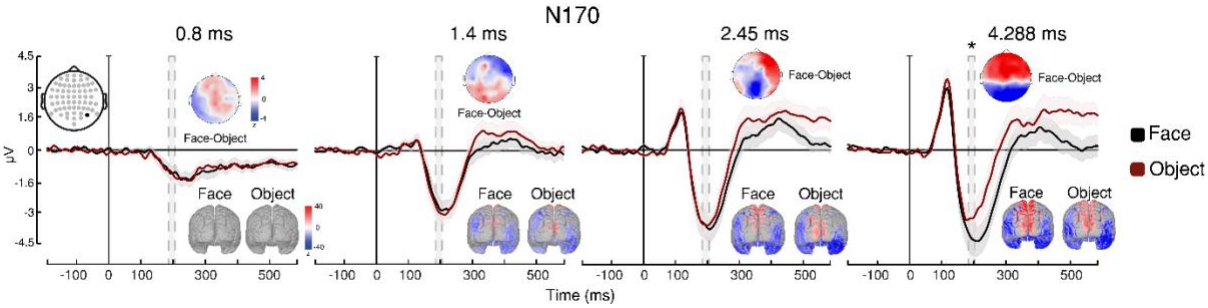

Fig. 3. Experiment 4: Neural measures of face vs. object processing. The N170, an ERP marker of face processing, discriminated between faces and objects only at the longest exposure. Topographic maps represent face – object voltage subtraction. Source estimation of the ERPs at their peaks are shown on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

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 minimal exposures 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 (*33*); furthermore, it is inconsistent with the proposal that

awareness of all stimulus attributes arises simultaneously (e.g., through 'ignition'; (*10*, *11*)). 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 (*19*, *34–36*), 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 (*37*, *38*). 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.

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