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Inflation versus filling-in: why we feel we see more than we actually do in peripheral vision

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Do we perceive fine details in the visual periphery? Here, we propose that phenomenology in the visual periphery can be characterized by an *inflated* sense of perceptual capacity, as observers overestimate the quality of their perceptual inputs. Distinct from the well-known perceptual phenomenon of 'filling-in' where perceptual content is generated or completed endogenously, inflation can be characterized by incorrect introspection at the subjective level. The perceptual content itself may be absent or weak (i.e. not necessarily filled-in), and yet such content is mistakenly regarded by the system as rich. Behaviourally, this can be reflected by *metacognitive* deficits in the degree to which confidence judgements track task accuracy, and *decisional* biases for observers to think particular items are present, even when they are not. In two experiments using paradigms that exploit unique attributes of peripheral vision (crowding and summary statistics), we provide evidence that both types of deficits are present in peripheral vision, as observers' reports are marked by overconfidence in discrimination judgements and high numbers of false alarms in detection judgements. We discuss potential mechanisms that may be the cause of inflation and propose future experiments to further explore this unique sensory phenomenon.

This article is part of the theme issue 'Perceptual consciousness and cognitive access'.

1. Introduction

How much of the visual periphery do we actually see? Some findings indicate that we perceive the periphery in precise detail [1] and that limitations in our ability to recall items are based mainly on memory, rather than sensory, processing constraints [2,3]. But findings from studies investigating inattentional blindness [4] and change blindness [5,6], despite being primarily designed to assess attended versus unattended items, provide some evidence that perception and memory of unattended items in the visual surround are quite limited. Thus, a question arises as to whether our subjective sense of the visual periphery is *inflated* beyond what we should expect based on the underlying processing limitations.

Two visual phenomena present unique opportunities to explain the puzzle of peripheral phenomenology: crowding and summary computations. Crowding is defined by deficits in the ability to identify objects surrounded by 'clutter' in the visual surround [7]. For example, identifying the middle letter in a row of three letters is relatively easy when they are presented in the centre of the visual field, but surprisingly difficult when they are shown in the periphery. Results reveal that crowding can change appearance [8,9], and therefore may be at least partially responsible for impairments in identifying objects in the periphery. Crowding can even result in metacognitive errors [10], indicating that it

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changes not only perceptual performance, but probably also subjective phenomenology [11–13].

Summary statistics are defined by the visual system's tendency to represent fine details in the visual periphery as an ensemble, as individual components are compressed into a gist-based representation [14]. This capacity for summary representation extends across a wide variety of dimensions, as observers can estimate the average size [15], motion direction [16], position [17] and orientation [18] of groups of elements quite effectively. It has been posited that summary statistics may underlie phenomenological experience of the visual periphery [19]. This view finds support in work using metamers [20], which shows that pooling mechanisms outside the fovea can cause distinct images to be perceptually indistinguishable. This demonstrates how distortions of peripheral visual content may not always result in subjective perceptual differences. And yet, introspectively, we do not seem to think we would fail to notice such distortions.

How can we characterize this mismatch between introspective phenomenology and representational quality in peripheral vision, to go beyond anecdotal descriptions? Traditionally, the mechanism of 'filling-in' is thought to be important and relevant. Filling-in is a perceptual phenomenon whereby features from surrounding regions of the visual field are perceived despite their physical absence in a particular location [21]. Typically, this is thought to be achieved by having the perceptual content in early sensory systems (e.g. V1) generated endogenously [22]. That is, actual content is created in the absence of external input. This can lead to illusory perception of colour [23], texture [24], motion [25], brightness [26] and other visual attributes. Filling-in is most evident in the blind spot, where the visual system compensates by representing similar content in this region without inputs [27], but is also evident in perceptual illusions like neon colour spreading [28] and the Troxler effect [29]. A related phenomenon can be found in the 'uniformity illusion', where under conditions of prolonged fixation, perceptual content from the fovea spreads to the periphery [30]. Evidence indicates that the neural mechanisms underlying filling-in reside in early-level visual areas [21,31–33], as early sensory representations are completed based on top–down rather than bottom–up input.

However, over and above the degree to which filling-in may play a role across the visual field, we hypothesize that a second process, *inflation*, also plays a role in perception of the visual surround. Inflation can be defined as the subjective overestimation of the reliability or quality of the sensory representations themselves. Similar to the notion of 'hyperillusion', where the 'appearance of appearance misleads about appearance' [34, p. 534], in inflation, the representations themselves are not necessarily filled in with details but are subjectively misestimated to be rich in content. Across the entire visual periphery, it is unlikely that filling-in processes provide all the fine details in early sensory regions in a precise, pixelated representation instantly as soon as we view a scene. In addition, there is evidence that even in cases where filling-in occurred, such as in the blind spot, there are additional subjective biases to be accounted for [35].

The concept of 'inflation' entails a prediction that our subjective introspection is impaired in some ways in the visual surround. Specifically, one way this could empirically play out is that subjective assessment of information presented outside the fovea will result in deficits in the capacity for metacognitive measures to track task performance, as the appearance of visual information in these regions does not correspond to the true reliability of the inputs. Alternatively, observers may have an increased tendency towards making false alarms when asked to detect specific perceptual content, as peripheral/unattended representations suffer from a decrease in the precision of encoding and the use of a relatively liberal perceptual criterion.

These ideas are based on previous empirical findings that included performance-matched conditions. In work by Rahnev *et al.* [36], performance was *matched* between attended and unattended conditions in tasks investigating perception of simple Gabor patches. When items were not attended, subjects used a more liberal detection criterion in a detection task and rated visibility to be *higher* for unattended items in a discrimination task. Similarly, in work by Solovey *et al.* [37], performance in a Gabor detection task was *matched* between central and peripheral presentation of stimuli, and subjects were shown to use a more liberal detection criterion in peripheral locations. Thus, to assess inflation in experiments, there are two aspects of behaviour that can be investigated: metacognition [36] and/or detection biases [37].

Because these two aspects can be captured with measures from signal detection theory (SDT), they can be readily characterized in quantitative terms in psychophysical experiments. Importantly, just because these biases are in terms of decision or confidence criteria does not mean they only reflect shifts in response strategy; it has been argued that these biases can reflect subjective perceptual phenomenology, which we interpret is probably also the case here [38,39]. In part, this argument is due to the observation that feedback and training did not seem to remove such biases [36]; if they were at the cognitive or response level, we would expect them to be more flexible and adaptive.

Previous work has already provided support for this inflation account for stimuli perceived under lack of attention. For example, according to [36], under conditions of inattention, representational precision of visual information is reduced, but a similar criterion is used compared to attended conditions, resulting in higher numbers of false alarms when making detection judgements [37], and higher ratings of visibility when making discrimination judgements [36]. Inflation can be interpreted to follow similar principles. In the visual periphery, processing capacity is reduced [40,41]. Similar to what has been shown under inattention, this may lead to an overestimated sense of how visible the periphery is, despite deficits in processing.

Here, to investigate the role that inflation may play in the periphery, we combined the study of crowding and summary statistics with SDT to quantitatively characterize whether inflation occurs in each of these scenarios. In our crowding study (Experiment 1; see §2), we assessed whether metacognition in a discrimination task is impaired in the periphery. Subjects performed a simple grating orientation discrimination task in both 'single' and 'crowded' conditions, and we analysed metacognitive efficiency in these conditions using the M-Ratio [42–44]. Lower metacognitive efficiency in the periphery may indicate that inflation has contributed to a failure to introspect correctly. In our summary statistical study (Experiment 2; see §3), subjects had to detect whether or not line patches included a group of lines with the same orientation. Our primary aim was to evaluate the prevalence of false alarm trials (i.e. the perceptual criterion used) for

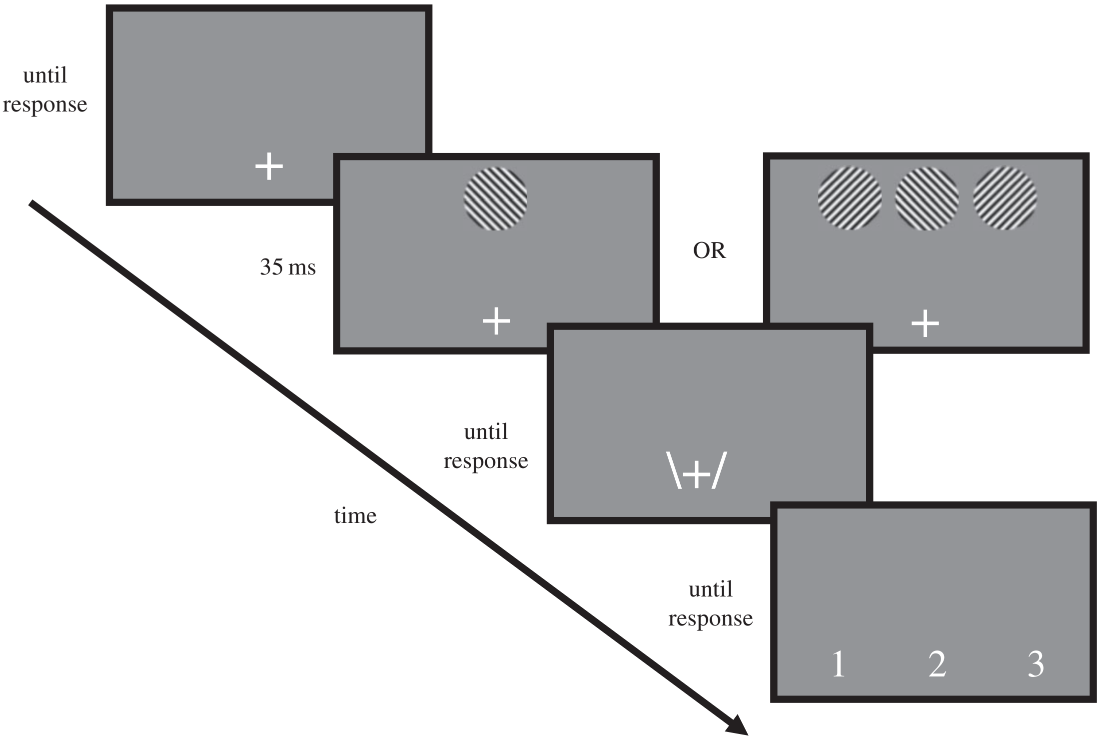

Figure 1. Protocol for each trial in Experiment 1. The fixation cross was shown throughout the trial. After participants pressed the 'space bar' on the keyboard to initiate the trial, the target sine wave gratings were presented above the fixation cross. This target grating could either be presented alone (single condition) or surrounded by other gratings on each side (crowded condition), and all patches were presented for 35 ms. Participants then had to report the orientation of the target patch (left or right) and also rate their confidence for their report on a scale of 1–3. We note that the sine wave gratings displayed in this figure are not to scale; we increased their size to improve appearance, but see §2a(ii) for details about size.

stimuli in central and peripheral locations. Evidence of a liberal perceptual criterion (i.e. more false alarms) in the periphery would provide a different line of evidence for the concept of peripheral inflation in the visual surround.

2. Experiment 1: Metacognition in crowding

In our first experiment, we explored how crowding, an omnipresent phenomenon in the visual periphery in everyday settings, may be linked to inflation. Specifically, we were interested in whether trial-by-trial confidence ratings would effectively track task performance, or whether these ratings would reveal impaired metacognition for elements in the visual surround (figure 1).

(a) Methods

(i) Participants

Thirty young adults (18–30 years old, $M = 22.00$, s.d. $= 2.95$; 25 females) with normal or corrected-to-normal vision were recruited from the University of Hong Kong to participate in this experiment. All participants volunteered and received no monetary compensation for their time spent in the experiment. This experiment was part of the second author's undergraduate thesis study and was approved by the Departmental Research Ethics Committee in the Department of Psychology at the University of Hong Kong. Informed consent was obtained from all participants before the experiment began. Twenty-three participants successfully completed this task. Among the seven participants that were excluded, five were excluded due to very low threshold differences between the crowded and single conditions, which indicates the absence of crowding (possibly due to unstable fixations), and two were excluded due to not following the instructions (one exhibited near-chance accuracy (less than 60%) and one exhibited a negative meta-d' score).

(ii) Apparatus and materials

Participants attended the experimental session in the Department of Psychology at the University of Hong Kong. The experiment was coded in MATLAB using the Psychophysics Toolbox [45–47] and custom-written code for stimulus presentation. Stimuli were presented on a 17-inch cathode ray tube (CRT) monitor (1024 × 768 pixel resolution at a 85 Hz refresh rate). Background luminance was 17.8 cd m^{-2} with ambient light turned off. A headrest and a chinrest were used to help the participants maintain a viewing distance of 92 cm.

Both target and flankers were sine wave gratings (2 cpd) presented through a circular window 2.5° in diameter. The orientation of the gratings was either 45° clockwise or 45° counterclockwise, both orientations had an equal probability of being displayed on a given trial. The target was presented 10° above the fixation cross, which subtended 0.3° and was presented near the bottom of the display. Two flanker gratings were presented left and right of the target at a target-flanker distance (centre-to-centre) of 3° in the crowded condition. This combination of target eccentricity and target-flanker distance was based on previous paradigms that showed robust crowding [48–50].

(iii) Procedure

After signing the informed consent form, participants were introduced to the task (figure 1). Participants performed an orientation discrimination task in each trial. Each trial started with the participants fixating on the fixation cross. Participants pressed (Space) to initiate stimulus presentation. Either the target alone (single condition) or the target with two flankers (crowded condition) was then presented for 35 ms. After the stimulus screen, two vertical lines tilted clockwise and counterclockwise were presented to the right and left of the fixation cross, respectively, to prompt the participants to respond using the number pad. Participants pressed (4) for left or (6) for right, and no feedback was given. After the orientation judgement, participants also reported their confidence in their judgement using a scale from 1 to 3. Participants were instructed that 1 indicated 'not at all confident', 2 indicated 'somewhat confident' and 3 indicated 'extremely confident'. Participants pressed (4) for 1, (5) for 2 and (6) for 3 in rating their confidence. Although we did not monitor eye movements in this experiment, the exposure duration we used was too short to execute a saccade from the fixation cross to the target.

Each trial block consisted of 64 single and 64 crowded trials. We used separate fixed-step-size staircases to continuously adjust the Michelson contrast levels for the two types of trials. A one-up one-down staircase with a down-step size to up-step size ratio of 0.2845 was chosen to achieve a target accuracy level of 77.85% [51]. There were two blocks of practice trials, followed by eight blocks of experimental trials. Participants performed only the orientation discrimination task, i.e. without the confidence rating, during the first practice block. Initial contrast levels were set at 0.4 and 0.8 for the single and crowded trials, respectively, in the first block. Staircases in blocks two to ten started with final contrast levels from the previous block. The SDT measures d' and meta-d' [42] were calculated based on blocks three to ten. If the staircases worked as planned, d' should be matched between the single and crowded conditions. However, our current set-up failed to render the required contrast levels (i.e. the contrast was not low enough for the single condition or the required contrast went beyond 1 for the crowded condition) for some participants. Therefore, we observed a statistically significant difference in d' between the single and the crowded conditions.

(iv) Analysis

Each participant's data were analysed using custom software for Signal Detection Theory (SDT) analysis [42,44,52]. Specifically, we used the fit_meta_d_MLE.m file to estimate both Type 1 (d') and Type 2 (meta-d') SDT parameters for sensitivity.

(b) Results

As shown in figure 2, participants displayed better performance (measured by the SDT measure d') in the single condition compared to the crowded condition, $t_{22} = 7.35$, $p < 10^{-6}$. Interestingly, participants displayed relative metacognitive impairments in the crowded condition compared to the single condition. We used the M-ratio to quantify metacognitive efficiency. The M-ratio, which is the fraction meta-d'/d', represents the amount of signal strength available for metacognition, and reflects the metacognitive efficiency in a given subject [42–44,53]. An M-ratio near 1 represents metacognitively ideal performance. As can be seen in figure 2, on average, participants were close to metacognitively optimal in the single condition; the small exceedance above 1 can be ascribed to estimation error or that they did not perform the primary discrimination task perfectly according to SDT. However, in the crowded condition, participants displayed clear metacognitive deficits, as the M-ratio was significantly lower in this condition compared to the single condition, $t_{22} = 4.26$, $p < 10^{-3}$. Thus, when experiencing crowding in the visual periphery, subjective assessments of how well we can see deviate from optimality. One could argue this may be due to the fact that, in the crowded conditions, d' itself was lower, and the M-ratio method may not have removed the influence of this difference perfectly, but the next result addresses this concern.

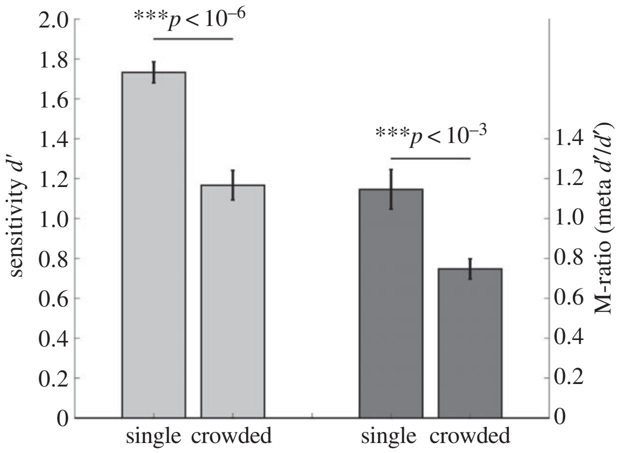

Figure 2. Perceptual sensitivity and metacognitive efficiency in an orientation discrimination task. Shown here are the results from 23 participants in Experiment 1. As shown by the light grey bars, participants were much less effective at discriminating the orientation of a tilted grating when it was surrounded by other gratings (the 'crowded' condition), compared to when it was presented alone (the 'single' condition). d' is the standard detection theoretic measure of sensitivity. The dark grey bars show a measure of the metacognitive efficiency (the M-ratio; meta-d'/d') in both conditions, which indicates how effectively confidence ratings could distinguish between correct and incorrect judgements. As can be seen in the figure, metacognitive efficiency was impaired in the crowded condition compared to the single condition.

To better illustrate the basis of this phenomenon, we also analysed average confidence in the single and crowded conditions, separating trials by whether they were correct or incorrect (figure 3). As can be seen in this figure, on *correct* trials, confidence was approximately the same between the single and crowded conditions, $t_{22} = -0.25$, $p = 0.81$. However, on *incorrect* trials, confidence was higher for the crowded trials compared to the single trials, $t_{22} = -8.46$, $p < 10^{-7}$. Notably, this higher confidence was shown despite the fact that people were overall less accurate in the crowded condition. Therefore, the deficit in metacognition in crowding seems to be primarily driven by overconfidence on incorrect trials: when participants are wrong about what they see in the periphery, they do not always know it, and have more confidence in their perception than what is warranted.

3. Experiment 2: Detection based on summary statistics

It has been proposed that part of what characterizes phenomenological experience of the visual periphery is the visual system's capacity to represent groups of items as ensembles

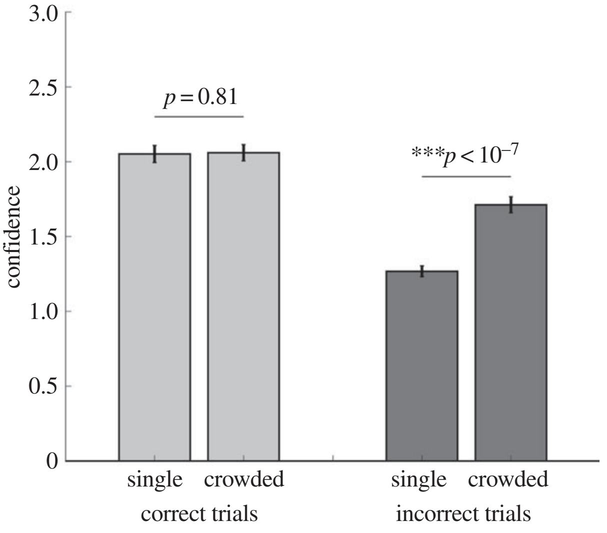

Figure 3. Average confidence for correct and incorrect trials. The light grey bars indicate the average confidence for correct trials for the single and crowded conditions. As can be seen in the figure, the difference between these conditions is not significant. The dark grey bars indicate the average confidence for incorrect trials. A clear difference between the single and crowded conditions is evident, and participants are significantly more confident in the incorrect crowded trials compared to the incorrect single trials.

or gist-based representations [19]. In other words, rather than encoding details in the periphery with high fidelity, visual information is compressed to eliminate redundancy and represent information outside the fovea in the form of summary statistics [14]. Considering the results from Experiment 1, it is an intriguing question how summary statistical judgement may be biased by the fact that individual crowded items may nonetheless provide a subjectively reliable percept, so that all the items together may subjectively look as if they are more coherent than they really are.

In Experiment 2, we investigated whether such detection biases exist in the periphery. On each trial, we presented observers with a diamond-shaped stimulus composed of many individual lines with various orientations (figure 4). We hypothesized that, similar to previous investigations, observers would be much more likely to say that a congruent patch of lines was *present*, even when the lines were composed of only random orientations.

(a) Methods

(i) Participants

A total of seventy-four research participants responded to an advertisement on Amazon's mTurk online platform and successfully completed the experimental task. Three participants were excluded due to errors in the fitting procedure from the MATLAB files for estimating signal detection parameters [52]. No personal or demographic information about participants was collected, with the exception of using each participant's unique Amazon mTurk ID to process payments. Research participants were informed before the study that it would require approximately one hour to complete, and that they would earn \$4 upon finishing the task, with the possibility of earning an additional \$1 bonus if their performance on the task was better than the previous participant. Participants were notified that they could drop out of the experiment at any time and were informed that they would be paid a prorated amount of \$1 per 15 min for the amount of time they participated in the study.

(ii) Apparatus and materials

We required all participants to use Google Chrome as their web browser for the experiment by adding code which excluded other browsers from running the task. Participants were informed of this requirement before beginning the experiment. The experiment was coded in JavaScript using plugins from the jsPsych library [54] and custom-written code for stimulus presentation. The psiTurk platform [55] was used to launch the study, administer subject payments, and control various elements of the task presentation and design (e.g. the hours when the task could be completed, the maximum time allowed to complete the task, enforce U.S. IP addresses for participants and other details).

(iii) Procedure

Following acceptance of our online 'HIT' (Human Intelligence Task) advertisement on Amazon's mTurk website, participants were presented with a consent form for the experiment, which was approved by the UCLA Institutional Review Board (#15-001484). Once participants agreed to the terms in the consent form, a new browser window was opened and participants began the main experiment. First, instruction screens were presented to request that participants be seated approximately one arm's length away from their computer screen, and to be positioned directly in front of the screen. Next, participants were informed of the experimental task.

Participants were instructed that they would be required to make judgements about a diamond-shaped pattern of 25 black lines drawn on a white background. Each line was 4 pixels wide and 30 pixels high and spacing between each line was 37.5 pixels on average, with a small amount of random jitter added to each position. Participants were asked to judge whether there was a group of lines that were all tilted in the same direction, or whether the lines were drawn only with random orientations. On trials where a group of lines with congruent rotations were shown, lines with random orientations were resampled if the randomly selected orientation was within 10° of the congruent orientation direction. Participants were informed that the group of lines with a common orientation could be any number of lines, and that the lines did not have to be next to one another to be considered part of the group.

The experiment began with practice trials to familiarize participants with the stimuli and task. To begin, three easy practice trials were presented where participants were shown the line stimulus for 2000 ms and then asked to indicate whether a group of lines were all tilted in the same direction. Participants pressed (Q) for Yes, and (P) for no, and were given feedback about whether the response was correct.

These three trials were followed by two 'practice' blocks of 60 trials each, where staircase procedures with fixed step sizes were implemented. The goal was to establish how many lines with coherent orientations should be presented for easy, medium and hard levels of difficulty, with these three levels designed to approximate ceiling-level performance, approximately 85% correct and approximately 71–77% correct, respectively [51,56,57]. In the first practice block, a two-up one-down staircase procedure [56] was implemented to estimate the 'hard' level of difficulty. Each

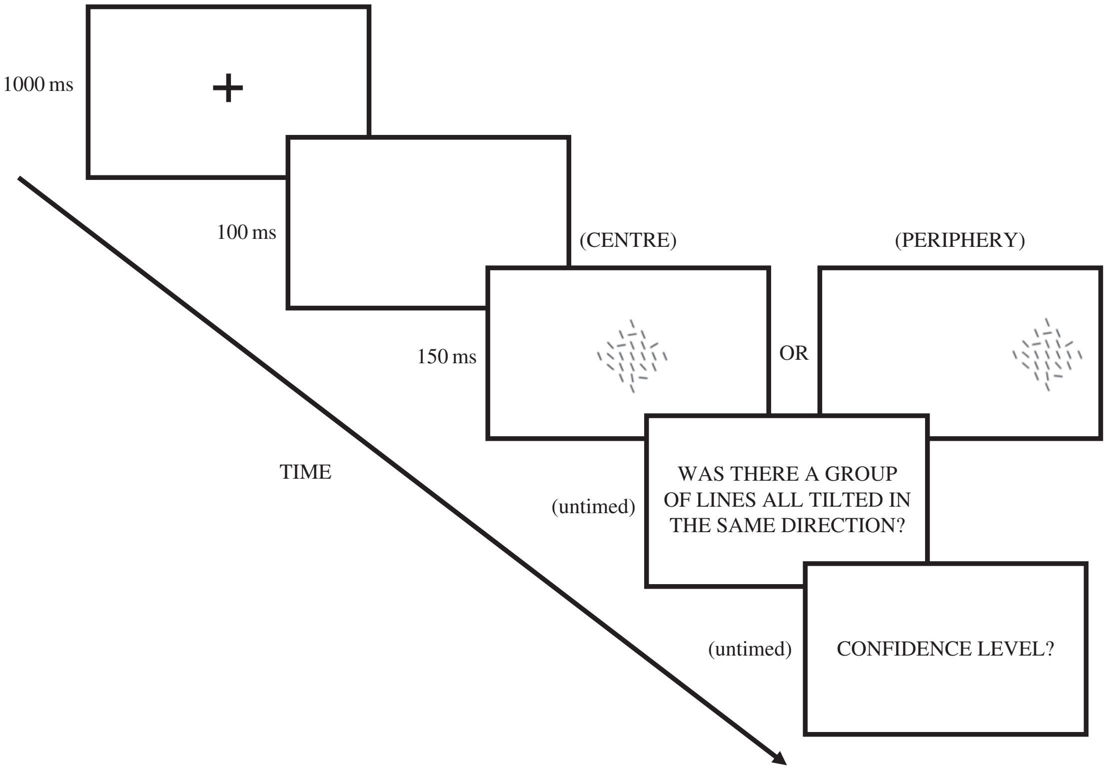

Figure 4. The protocol for each trial in Experiment 2. Each trial began with a fixation cross for 1000 ms, followed by a 100 ms blank screen. Then, lines were presented at either a central or peripheral location for 150 ms. Following presentation of the lines, participants responded whether a group of coherent lines with the same orientation was present and rated their confidence on a scale of 1–4. In this example, there are 16 lines with congruent orientation in the image. Please note that the wording shown in this schematic differs slightly from the actual wording displayed in the experiment.

trial began with a fixation cross presented at the centre of the screen for 1000 ms. Following a 100 ms blank screen, one group of lines was flashed at the location of the fixation cross for 150 ms; 800 ms later, another group of lines was flashed for 150 ms at the same location. Participants were informed in advance that only one of the two sets of lines contained a group tilted in the same direction and had to indicate whether the first or second presentation contained the coherent group by pressing (Q) or (P) to indicate the first or second presentation, respectively. Participants were also informed that these practice blocks counted towards whether they earned the bonus, to increase incentive to put forth effort as the staircase was implemented. In the second practice block, a four-up one-down staircase procedure was implemented to establish stimuli that could be used for the 'medium' level of difficulty, and the same protocol as the hard staircase was used for each trial. For the 'easy' level of difficulty, 20 coherent lines were presented, and no staircase was used to estimate this level. Conditions were included so that the number of coherent lines in the 'hard' condition could not exceed 16, and the number of coherent lines in the 'medium' difficulty condition could not exceed 18.

Following the staircase estimations, the real experiment began (figure 4). In all trials, first, the fixation cross was presented at the centre of the screen for 1000 ms. Following a 100 ms blank, a single group of lines was presented for 150 ms at either the centre of the screen, or in a peripheral location along the same horizontal meridian, 360 pixels away. To discourage participants from starting with their eyes anywhere other than the fixation cross, 50% of trials presented the lines at the centre, 25% of trials presented the patch of lines in a peripheral location on the left and 25% of trials presented the lines in a peripheral location on the right. After the lines disappeared, participants were required to indicate whether or not there was a group all tilted in the same direction (by pressing Q or P, respectively), and following this, were also required to rate how confident they were in their responses, on a scale from 1 (not at all confident) to 4 (extremely confident).

There were 360 total trials in the main experiment; 180 trials were presented at the centre, and 180 trials were presented in peripheral locations (90 left, 90 right). Within each condition (centre/periphery), 60 trials were of easy difficulty, 60 medium difficulty and 60 hard. Catch trials were added at four different trial markers in the experiment (40, 120, 200 and 280). During a catch trial, a letter was displayed at the centre of the screen for 1000 ms. After the letter disappeared, participants were asked whether an a, b, c or d was displayed, and were required to input a response on the keyboard. Participants were instructed to take a break for at least 30 s after trials 80, 160, 240 and 320.

(iv) Analysis

Each individual participant's data were analysed using custom software for Signal Detection Theory (SDT) analysis [42,44,52]. We used the SDT_MLE_fit.m file to estimate basic Type 1 SDT parameters for sensitivity (d_a) and bias (i.e. the criterion, c_a) for the aggregated data across all three difficulty levels, and a modified version of the type2_SDT_SEE.m to compute the hit rates and false alarm rates. In Experiment 1, we used the standard SDT measure d' because in a discrimination task of that nature, it is unlikely that the equal variance assumption for the two stimulus representations was violated. However, in detection tasks this tends to be an issue. Thus, we used the measure d_a to account

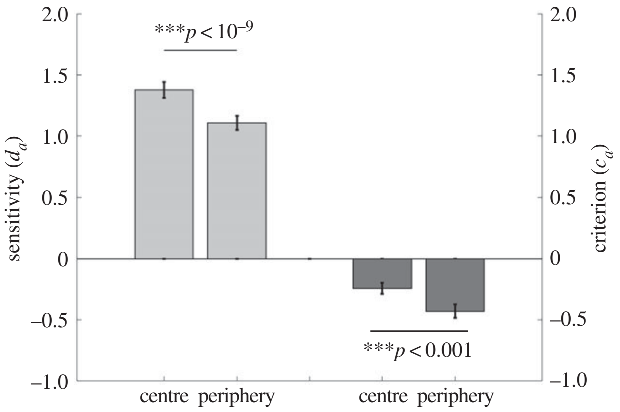

Figure 5. Sensitivity and bias for detecting congruently oriented groups of lines. Shown here are results from an experiment where participants were asked to detect whether a group of lines with congruent orientations were presented, in either a central or peripheral location. As shown by the light grey panels, using the measure d_a (which corrects potential unequal variance in detection tasks), participants were more sensitive in detecting the congruent patch of lines at the central location compared to a peripheral location, and yet they used a more liberal criterion c_a in the periphery for indicating that a patch of lines was present. Note that although sensitivity is not perfectly matched between centre and periphery, usually we expect subjects to be relatively conservative for weaker detection, based on the Neyman–Pearson objective [58,60]. Therefore, the results are striking in that they were in the opposite direction to that expectation.

for potential differences between the variances of the signal and noise distributions [58,59].

(b) Results

As shown in figure 5, participants were more sensitive (i.e. exhibited higher d_a) in detecting whether a group of lines with congruent orientations was present in the central part of the screen (at fixation), compared to when lines were presented at peripheral locations, $t_{70} = 7.39$, $p < 10^{-9}$. Participants also used different criteria for evaluating whether a coherent patch of lines was present at the centre of the screen or the periphery. Specifically, participants were more liberal in detecting coherence in the periphery compared to the centre, as shown in the differences in c_a, $t_{70} = 3.89$, $p < 0.001$. This resulted in a higher number of false alarms (responding ‘yes’ when only random lines were presented) in the periphery compared to the centre.

Specifically, on trials where lines with only *randomly sampled* orientations were shown and participants incorrectly reported that a congruent patch was presented (i.e. false alarms), results revealed that participants were much more likely to incorrectly respond when the lines were presented in the periphery, compared to trials where the lines were presented in the centre, $t_{70} = -6.80$, $p < 10^{-8}$ (figure 6). No difference across conditions was found in trials where a coherent patch was presented and participants correctly responded, $t_{70} = -0.79$, $p = 0.43$.

These results conceptually replicate previous studies showing that observers use liberal perceptual criteria when making detection-related judgements in the periphery [36,37], and indicate that this liberal detection criterion is used for not only detecting simple stimuli like Gabor patches, but also for more complex stimuli involving summary statistics.

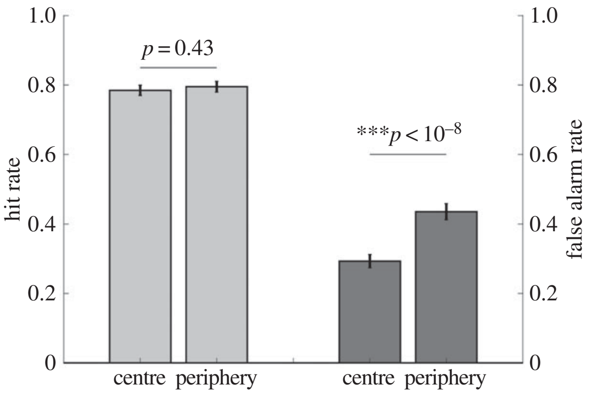

Figure 6. Hit rate and false alarm rate for detecting congruently oriented groups of lines. In this figure, the light grey bars along the left axis denote the hit rate (i.e. correctly responding that a group of lines with similar orientation was presented) and the dark grey bars along the right axis display the false alarm rate (incorrectly indicating that a group of lines with similar orientation was shown, when only random lines were presented). While the hit rate for detection in this task was quite similar across the two conditions, the false alarm rate was significantly higher in the peripheral condition compared to the central condition.

4. Discussion

We considered how peripheral visual perception may demonstrate *inflation*, whereby subjective judgements in this region of space are marked by two behavioural characteristics: *metacognitive impairments* in how effectively confidence judgements track the correctness of responses in experimental tasks, and *decisional biases* in observers’ tendencies to assume stimuli are more likely to be presented in the periphery than what actually occurs. We conducted two experiments to investigate whether these deficits would emerge in tasks that exploit two well-established phenomena in the visual surround: crowding and summary statistics. In our first experiment using crowded stimuli, observers showed relative deficits in a metacognitive measure (e.g. the ‘M-ratio’) [44,53] for crowded compared to single stimuli. This metacognitive deficit was primarily driven by overconfidence in incorrect responses, which is striking given that subjects did not perform the primary discrimination task very well under crowding; the overconfidence is highly unwarranted. In our second experiment using a summary statistical stimulus (groups of oriented lines), observers exhibited liberal detection criteria and high numbers of false alarms, showing that decisional biases extend to more complex stimuli than has been previously shown. Both of these findings provide experimental evidence that, far from perceiving the visual periphery with a high degree of fidelity [3,61,62], our subjective sense of the visual surround is inflated.

These findings speak to the debates surrounding ‘access consciousness’ [34], specifically, whether phenomenological content overflows cognitive access [3,63,64]. Previous work has identified that often we have a ‘feeling of seeing’ that goes beyond what is actually perceived [65], and overall evidence for true phenomenological overflow remains equivocal [66]. While some evidence points to the existence of rich, rapidly decaying visual information outside the fovea [2], our findings here suggest that our subjective assessment in the periphery may not be perfect. Importantly, it may not just be a matter of capacity, but could be a form of bias, too.

Our findings on inflation also go beyond what has been shown previously. Research has shown that under sensitivity-matched conditions, inflation occurs under inattention and in the periphery [36,37] for simple stimuli, such as Gabor patches. In the present research, sensitivity was not matched, but the stimuli were optimized to exploit the characteristics of peripheral vision, with multiple inputs incorporated simultaneously. These conditions capture the everyday challenges faced by peripheral vision: a deluge of inputs and inherent processing limitations. Under these conditions, the lower sensitivity in crowded/peripheral conditions is expected to result in more conservative detection criteria and lower confidence, but the results strikingly showed the opposite effects. These results demonstrate the prevalence of inflation: it happens also when we did not contrive to fully compensate for the reduced sensitivity in the periphery (by presenting it with stronger stimuli). Inflation is present in various scenarios, including when more complex stimuli are used to challenge the processing bottleneck in peripheral vision. Because crowding and summary statistical judgements happen often in the periphery in everyday life, if inflation is more easily observed in these paradigms than in typical psychophysical experiments involving single targets, the phenomenon may be more prevalent than previously thought [62].

One difference between the present work and previous studies [36,37] is that in our second experiment, our peripheral stimulus incorporated elements of both endogenous and exogenous attention. That is, the peripheral stimulus carried inherent locational uncertainty as it could arise in one of two locations, and this uncertainty probably resulted in not only trial-to-trial differences in the allocation of endogenous attention, but also how exogenous attention may have played a role, too, when the stimulus was presented. That may also explain why the effect of inflation was robust even though sensitivity between centre versus periphery was not matched. Future investigations should aim to systematically investigate how exogenous attention and endogenous attention may alter the characteristics of inflation that we observed here.

These findings raise an important question: what may be a mechanistic explanation for inflation? Previously, one proposed account based on SDT was the variance reduction model [36]. According to the model, inattention and peripheral presentation do not drastically alter the perceptual criteria used to make judgements; therefore, the increased variance in internal response in these circumstances causes a greater frequency of occurrences where the response crosses a detection or confidence criterion. Although there are caveats as to whether the criteria are really so inflexibly fixed [67], the model has also been directly tested and highly counterintuitive predictions have been confirmed [68]. Nevertheless, we acknowledge the simplistic nature of this model. Future work is needed to further elucidate a biologically realistic mechanism.

One potential concern is that based on the results from our first experiment, one could argue that all we observe is a change in confidence, and that the link between confidence and perceptual phenomenology is tenuous. While we acknowledge that confidence is not synonymous with phenomenology *per se*, and some prefer other methods of assessing perceptual experience [69–73], there are many cases where confidence provides an effective assessment of phenomenology's presence or absence. For example, in blindsight patients, visual task performance is often spared but phenomenology is not, and confidence ratings provide an effective means to assess the absence of experience of visual content [74,75]. But we note that even when we ask non-metacognitive questions, as in our second experiment, results indicate that observers think they see more of the periphery than they actually do. It is the joint observation, that peripheral perception leads to both erroneous overconfidence and liberal detection bias, that led us to think these findings may be relevant for subjective phenomenology.

Also, we interpret these findings to reflect inflation, but this is not to say we fully rule out an interpretation based partially on filling-in. Although sensitivity was lower in peripheral detection as well as crowding, such low sensitivity could be the result of filling-in of illusory (i.e. non-veridical) content. Filling-in undoubtedly occurs in the blind spot in the periphery, but it would seem improbable if the content for the entire periphery were always automatically and instantly filled in across the visual field, as these systems are subject to limited resources. Even if some details are filled in in the periphery, it is clear that they are not being filled in correctly, as sensitivity was not better in the crowded/peripheral conditions in our experiments. Overall, our point here is that over and above potentially filling-in, inflation is probably also at work, and its role in accounting for phenomenology in the periphery is at least as important [35].

To further probe the phenomenon of inflation, it may be worthwhile in future investigations to probe how the detection criterion changes in blindsight experiments. Additionally, future experiments should investigate if the metacognitive deficits identified in Experiment 1 scale with eccentricity, as it seems plausible that the magnitude of these effects may increase as distance from the fovea increases.

Finally, it is worthwhile to question why inflation occurs in the visual system. We posit that this effect may be related to ideas regarding 'self-consistent perception' [76,77]. That is, after an observer is forced to make a decision about a given stimulus property in the world, the observer discards all potential estimates that are not in agreement with the choice, performing inference conditioned only on the decision made. This leads to a repulsive bias away from the perceptual decision boundary. Computational accounts drawing upon Bayesian inference and efficient coding have accounted for these perceptual effects for low-level attributes like orientation and spatial frequency quite well [78,79], and we posit that something similar may be happening for other phenomena like colour in the periphery: based on the foveal representation, perceptual systems infer that the world is colourful and rich; it seems plausible that the perceptual system then infers a rich colourful representation *across* the visual field, even when such an inference is unwarranted because the content in peripheral areas is sparse. Additionally, because we make saccades frequently in natural settings, having such biases can also enhance the consistency of our subjective impression of the world over time.

Additionally, when considering the decisional bias that is present, it becomes important to reflect on what cost functions the visual system may be trying to optimize [80]. A liberal detection bias that causes higher numbers of false alarms may not be 'optimal' according to strict signal detection theory. However, in a dynamic, changing world that requires fast identification of objects for survival, perhaps a slight overestimation of the presence of objects in the periphery is optimal in the sense that identification of potential threats or rewards can spur exploration and action, to avoid predators and find food and mates. These liberal detection biases may also reflect a larger tendency of perceptual and cognitive systems to make high numbers of false alarms for not only attributes like presence or absence, but also agency in situations where none exists [81]. Overall, these considerations may account for why we subjectively perceive the visual world as relatively uniform despite the poor sensitivity in the periphery.

Ethics. All research in Experiment 1 was approved by the Departmental Research Ethics Committee in the Department of Psychology at the University of Hong Kong. Experiment 1 was an undergraduate thesis. All research in Experiment 2 was performed under UCLA IRB #15-001484 and was conducted in accordance with the Declaration of Helsinki.

Data accessibility. All code and datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' contributions. M.Y.C. and S.-H.C performed the data collection and main analyses for Experiment 1. B.O. conducted the final statistical analysis and created figures for Experiment 1, and performed the data collection, main analyses and figure creation for Experiment 2, under the guidance of H.L. B.O., M.Y.C., H.L. and S.-H.C. wrote the paper.

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