Introduction

To maximize the efficiency of sensory processing, our visual system relies on foreknowledge to prioritize the processing of relevant or expected features. For example, knowledge of statistical regularities in the environment can lead to faster recognition of objects when they are encountered in an expected context (e.g., a bird in a backyard) than when they are encountered in unlikely context (e.g., a bird in a washing machine; Biederman, Glass and Stacy, 1973; Biederman, Mezzanotte and Rabinowitz, 1982; Geisler, 2008; Summerfield and de Lange, 2014; Rungratsameetaweemana *et al.*, 2018). In addition, knowledge about the current task goals can also support faster and more accurate processing of relevant over irrelevant items a mechanism referred to as selective attention (Carrasco, 2011; Rungratsameetaweemana and Serences, 2019; Summerfield et al., 2008). Importantly, these two types of "top down" modulatory factors are potentially dissociable, as the probability that a stimulus will be encountered in a specific context is not necessarily linked to its behavioral relevance (Firestone and Scholl, 2015, 2014; Lupyan, 2017, 2015; Newen and Vetter, 2017; Summerfield and de Lange, 2014; Summerfield and Egner, 2009; Summerfield and Tsetsos, 2015).

Over the last several decades, numerous studies have demonstrated that attention improves the efficiency of perceptual processing by modulating the gain of neural populations with respect to current task demands (Carrasco, 2011; Desimone and Duncan, 1995; Reynolds and Chelazzi, 2004; Serences and Kastner, 2014; Itthipuripat and Serences, 2015; Itthipuripat et al., 2014a; 2014b, 2017; 2018; Hillyard and Anllo-Vento, 1998; Hillyard et al., 1998). Prior expectation, in contrast, has only recently been explicitly investigated as a potentially separable mechanism that might also bias early sensory processing in favor of stimulus with high probability (Summerfield and de Lange, 2014; Summerfield and Egner, 2009). Based on behavioral and neural evidence collected from tasks paradigms where prior expectation of stimulus features was manipulated through a probabilistic cue, past studies suggest that expected stimuli evoke a more precise feature-selective pattern of responses in primary visual cortex, leading to more efficient processing (Kok et al. 2012; Kok et al. 2013; Wyart et al. 2012; Summerfield & de Lange 2014; Cheadle et al. 2015; Aiken et al., 2020). However, this cueing paradigm possibly conflates the theoretically distinct notions of prior expectation (e.g., where a stimulus is likely to appear) and selective attention (e.g., which spatial location is likely to contain information relevant to the current task). Therefore, any influence of the cue on information processing, either behaviorally or neurally, is difficult to attribute to either top-down factor or to some combination of the two.

Expectation and attention can be dissociated by adopting a Bayesian account of perceptual inference that takes into account the precision of existing beliefs (i.e., prior) as well as the precision of the sensory information (i.e., the likelihood function). Specifically, expectation about stimulus regularities should modulate the precision of priors while attention based on behavioral relevance of the stimulus should modulate the precision of the likelihood function. Based on the Bayesian framework, attention and expectation should also have the strongest influence on perception when sensory evidence is weak and prior knowledge about both stimulus identity and relevance is needed to supplement sensory information (Chalk et al., 2010; de Lange et al., 2018; Sterzer et al., 2008; Summerfield and de Lange, 2014). Thus, while both expectation and attention clearly impact overall behavioral performance, it is possible that these two factors differentially influence information processing and decision making at different processing stages and at different time scales.

- Note:
    - Different stages   the nature of how prior knowledge can influence perception/cognition
    - Their interaction with bottom-down   more complete picture
    - Temporal dynamics both neurally and behaviorally   tightly linked with behavioral (more realistic/ continuous response)

To investigate these questions, the strength of prior knowledge (expectation) and the behavioral relevance of competing stimuli (attention) have to be independently manipulated. Several recent studies have at least partially achieved this goal by inducing expectation without using an explicit probability cue that carried information about the behavioral relevance of the target. These reports showed that expectations did not impact early sensory processing but instead modulated later cognitive operations including response criteria as well as the selection and execution of motor responses (Bang and Rahnev, 2017; Rungratsameetaweemana et al., 2018). However, these studies did not manipulate attention and little is known about the temporal dynamics of attention and expectation, interactions between these factors, or about their interaction with the strength of sensory evidence to influence different stages of sensory processing and decision making.

The present study examined these questions be devising a continuous orientation discrimination task where expectation, attention, and stimulus strength were manipulated orthogonally. Each trial started with an attention cue to indicate whether participants had to monitor one (focused attention) or two patches (divided attention) of flickering bars to detect a target coherent orientation. Expectation was implicitly manipulated on a block-by-block basis such that the targets on each block were predominantly presented at one orientation. Stimulus strength was manipulated through the coherence level of the flickering bars that defined the target coherent orientation. Participants reported the coherent orientation using a flight simulator joystick which enabled a continuous measure of responses over time. Electroencephalography (EEG) was concurrently recorded while participants performed the task. With this experimental design, we were able to 1) isolate the impact of stimulus strength, attention, and expectation on behavior; 2) examine the temporal dynamics of these factors behaviorally through response trajectories and response error across time as well as neurally through EEG markers of early sensory processing and steady-state visually evoked potentials (SSVEP) which track processing of feature-specific information during decision making.

Graveyard:

- how it is fused to determine behavior on short time scales, and how it is used to adapt, refine, and learn behaviors on longer time scales.
- Coordinated work in theory, modeling and experiment will be required to understand the mechanisms of context-dependent information flow in the brain, which lies at the heart of flexible behaviors such as decision-making.
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- There is reason for caution, however. The number of apparent dimensions in the data may be artificially low if the behavioral task is too simple or if neuronal activity is not measured for sufficiently long periods of time. Thus it is essential not only to record more neurons, but to also increase behavioral and stimulus complexity in order to obtain richer, higher dimensional data sets.

Results

The main goal of the present study was to manipulate and examine the effects of stimulus strength, changes in the distribution of selective attention, and expectation about stimulus regularities on perceptual decision making. We used trajectories of behavioral responses and response errors as behavioral markers of sensory and post-sensory decision-related processes, respectively. Further, we used ERPs from the centro-parietal to occipital electrodes and SSVEPs as neural markers of sensory encoding and early processing of sensory information during perceptual decision making. If prior expectation improves decision making by enhancing the efficiency of early sensory processing, we expect to see increased ERP and SSVEP responses over visual cortex. However, if expectation improves decision making by primarily modulating decisional and response-related processes, we expect to see little impact of expectation on ERP and SSVEP responses. With our experimental setup, we were able to directly test this hypothesis as well as to future investigate and compare the temporal dynamics of expectation with those of stimulus strength and attention both behaviorally and neurally.

Behavioral results

High target coherence and focused attention enhanced early sensory processing as indexed by trajectories of behavioral responses. The response trajectory indicated the distance the joystick had moved from the center at each time point (0 to 1300 ms after the onset of coherent orientation). Notably, this measure represents a temporal integration of sensory information about the coherent orientation as participants accumulate evidence that eventually leads to a decision choice. The coherence level of the target orientation displays (high/low) affected response trajectories from 675 to 1200 ms after the onset of coherent orientation (high > low coherence; all resampled $p < 0.05$; Fig. 2a). Similar to high target coherence, focused attention also enhanced the amplitude of response trajectories but its effect emerged much earlier in time (266.7 to 966.7 ms after the onset of coherent orientation; all resampled $p < 0.05$; Fig. 2b). Response trajectories were not modulated by manipulations of expectation (Fig. 2c). Fig 2d summarizes the effects of target coherence, attention and expectation. Fig. 2e shows the p values for each condition and at each time point (500 ms before the onset of coherent orientation to 1300 ms after the onset; all resampled $p < 0.05$).

Expectation modulates biases baseline responses error. Response errors were computed as the absolute difference at each time point between the participant's response orientation and the calibrated orientation for that participant (see **Methods**). The amplitude of the response errors at each time point indexes the accuracy of the orientation judgment of participants, which primarily reflects response-related operations. The coherence level of the target orientation affected performance accuracy such that high orientation coherence decreased responses errors from 541.4 to 1300 ms after the onset of coherent orientation and from 225 ms before peaked response to 250 ms after peaked response (resampled $p < 0.05$; fig. 2f). Similarly, focused attention also led to lower response errors from 691.7 to 716.7 ms after target onset (resampled $p < 0.05$; fid. 2g). In contrast, expectation enhanced baseline performance accuracy such that response errors were lower when the target coherent orientation was expected. This effect was observed from 500 ms before target onset to 833.3 ms after target onset (resampled $p < 0.05$; fig. 2h). Additionally, response errors were lower on expected trials from 500 ms to 133.3 ms before the peaked responses (resampled $p < 0.05$; fig. 2h). Fig 2i summarizes the effects of target coherence, attention and expectation. Fig. 2j shows the p values for each condition and at each time point (left panel: 500 ms before the onset of coherent orientation to 1300 ms after the onset; right panel: 500 ms before to 250 ms after the peaked response; all resampled $p < 0.05$).

- Violins
  - -250 to 0 ms tg-locked: exp effect p = 0.014
  - 500 to 750 ms tg-locked: exp effect p = 0.001, coh p = 0.03
  - Resp locked: 1) -500 to -250 ms resp offset locked: coh 0.049; exp = 0.046
  - At peaked response: coh p = 0
- Something to think about based on Sara Solla's talk: behavioral stability (through response trajectory)

Interactions:

- When compare the size of expectation effect under different levels of sensory evidence (hi exp – hi un vs lo exp – lo un), we see that 1) comparable expectation effect size before target onset, which makes sense because target hasn't come up yet so the amount of sensory evidence doesn't matter at this point; 2) after target onset, the effect of expectation in the low coherence condition, emerges much faster than in the high coh condition, showing that once that target comes up in the low coh, it's hard so subjects relied on their learned expectation leading to an earlier drop in response error.
- When compare the size of sensory evidence effect on exp vs unexpected trials (hi exp - lo exp vs hi un – lo un), we see that 1) there's no difference before target onset which is good (because we are not comparing across different level of expectation); 2) the effect of coherence comes up earlier in on the expected trials, this just shows that people successfully learned and used expectation to guide their response by combining it with low level sensory info (lo/hi coherence).
- 01/15/2021: RT1 and RT2 has effects on coh and att and also interactions

EEG results

Expectation does not modulate the efficiency of early sensory processing. We used ERPs recorded from the centro-parietal (Cpz), parietal (Pz), parieto-occipital (POz), and occipital (Oz) electrode to index the magnitude of early sensory processing during a perceptual decision making task. We analyzed the effects of target coherence, attention, and expectation on the amplitude of target-aligned ERPs in sliding 50 ms windows and corrected for multiple comparison using FDR method based on target-aligned data from CPz, Pz, POz, and Oz electrodes (see **Methods**). Manipulations of target coherence and attention directed to target coherent orientation influenced ERPs across all four electrodes at different time scales.

Focused attention induced early changes in the ERP responses across all channels (CPz: target onset to 500 ms after target onset; $t_{(12)}$ = 3.24-5.01; p = 0.0003-0.0071; Cz: target onset to 450 ms after target onset; $t_{(12)}$ = 3.17-4.67; p = 0.0005-0.0081; POz: target onset to 100 ms and 150 to 250 ms after target onset; $t_{(12)}$ = 4.04; p = 0.0016; Oz: target onset to 50 ms after target onset; $t_{(12)}$ = 3.70; p = 0.0031, FDR-corrected threshold = 0.0106; Fig. 3b). The effect of orientation coherence occurred later in time (CPz: 450 to 1000 ms; $t_{(12)}$ = 3.34-4.54; p = 0.0007-0.0058; Cz: 500 to 850 ms and 900 to 1000 ms; $t_{(12)}$ = 3.01-4.59; p = 0.0006-0.0109; POz: 950 to 1000 ms; $t_{(12)}$ = 3.19-3.29; p = 0.0065-0.0077; Oz: 400 to 450 ms after target onset; $t_{(12)}$ = 3.03; p = 0.0105, FDR-corrected threshold = 0.0123; Fig. 3a). ERP responses were not affected by manipulations of expectation.

SSVEP

We assessed SSVEPs from three different time windows: i) from 500 ms before target onset to target onset; ii) from target onset to 500 ms after target onset; and iii) fron 500 ms to 1000 ms after target onset. High orientation coherence increased SSVEP amplitude from 200 ms to 250 ms after target onset ($t_{(12)}$ = 3.85; p = 0.0023; FDR-corrected threshold = 0.0023; Fig. 4a). Manipulations of attention also affected SSVEP responses such that focused attention enhanced SSVEP amplitude from 250 ms to 50 ms before the onset of coherent orientation ($t_{(12)}$ = 3.40-4.44; p = 0.0008-0.0053; FDR-corrected threshold = 0.0053; Fig. 4b). In contrast, expectation had no effects on SSVEP responses. Notably, this pattern of results was similar to what was observed in ERPs with the early modulation of focused attention that was followed by the effects of orientation coherence. In addition, the lack of expectation effects was consistent on both the ERP and SSVEP responses.

Figure 4 a, b, c

- SSVEP amplitude on high coherence trials was higher than that on low coherence trials across all three time windows (window 1: $t(12) = 3.12$; $p = 0019$; window 2: $t(12) = 25.13$; $p < 0.001$; window 3: $t(12) = 11.94$; $p < 0.001$).
- SSVEP amplitude on focused attention trials was higher than that on divided attention trials 500 ms before and 500 ms after target onset (window 1: $t(12) = 20.62$; $p < 0.001$; window 2: $t(12) = 23.65$; $p< 0.001$).
- SSVEP amplitude on unexpected trials was higher than that on expected trials across all three time windows (window 1: $t(12) = 22.62$; $p < 0.001$; window 2: $t(12) = 24.08$; $p < 0.01$; window 3: $t(12) = 34.42$; $p < 0.001$).

Discussion

In past studies, expectation was manipulated in a way that likely induced a shift in attention, making it difficult to attribute any observed effects on early sensory processing to expectation per se or to some combination of expectation and attention. For example, a recent study used fMRI and a task where expectation about a target orientation (45° or a 135°) was manipulated by an explicit cue presented at the beginning of each trial (Kok et al., 2012). This cue provided information about what target feature to expect on each trial, but simultaneously provided information about which target feature was relevant to performing the behavioral task. Similar arguments can be made regarding other studies that examined the influence of expectation on decision making (Kok et al. 2013; Kok et al. 2016; Kok et al. 2017; St. John-saaltink et al. 2015; Lange et al. 2013; Jiang et al. 2013; Cheadle et al. 2015; Summerfield & Egner 2016). A few studies have taken a further step to examine how expectations about stimulus regularities interact with attention to modulate information processing, it is difficult to interpret their findings due to a possible conflation of these two top-down signals as a result of the use of explicit probabilistic cues (Jiang et al., 2013; Wyart et al., 2012). Therefore, the selective role that expectations play in early sensory processing, and also how expectations interact with attention to modulate the overall flow of information through the visual system remains unclear.

The present study investigated these questions by devising a continuous orientation discrimination task where expectation about coherent orientation was manipulated such that one (expected) orientation was presented as a target more frequently than other (unexpected) orientations. Stimulus strength and the degree of attention being afforded to the relevant stimulus were also orthogonally controlled for. As a result, the impact of expectation could directly be compared to the effects of stimulus strength and to the effects of selective attention. Specifically, we directly tested whether expectation about stimulus probabilities improved decision making by enhancing the efficiency of early sensory processing. Behaviorally, we showed that expectation did not impact response trajectories—a behavioral measure that primarily reflects sensory processing and temporal integration of sensory information leading up to a decision choice. In contrast, response trajectories were modulated by stimulus strength and attention such that high orientation coherence and focused attention increased the amplitude of response trajectories. Specifically, the effect of attention occurred earlier in time compared to the effect of orientation coherence. These temporal dynamics were also observed in our ERP and SSVEP results suggesting early processing of sensory information in our decision-making task is sequentially modulated by selective attention and stimulus strength leading up to a decision choice. Once a decision choice has been triggered, the response-related operations to execute a motor response is modulated by prior expectation such that the response associated with a more probable choice is preferred and thus will take less time to execute.

Taken together, our behavioral results reveal that prior expectation improves perceptual decision making as by shifting baseline response errors and thus increasing performance accuracy without impacting early processing of sensory information. This evidence for a selective role of expectation on decisional and response-related processes was consistent with the lack of expectation effects on the neural markers for sensory processing of information throughout the visual cortex.

Methods

Participants

Thirteen healthy volunteers (seven males; all participants right-handed; mean age = 20.5, SD = 2.3) participated in the experiment. All were neurologically intact and had normal or corrected-to-normal color vision. Participants provided written informed consent and were compensated $10 per hour for participation. Ethical approval was granted by the Institutional Review Board at the University of California, San Diego. Each participant underwent 4 behavioral sessions (sessions were approximately 1.5 hours each, with 5376 trials collected in total).

Stimuli

For each of four test sessions, participants completed a block of practice trials (n = 120 trials), a block of calibration trials (n = 120 trials), and 20 test blocks (n = 120 trials each block). For the practice trials and the main task, stimuli consisted of 200 red bars and 200 blue bars displayed in an annulus (outer diameter, 22°; inner diameter, 2.4°) that surrounded an attention of either red, blue, or green on a dark gray background of 42.682.20 cd/m^2 (Fig. 1). Red and blue bars within the annulus were flickered either at 30 Hz or 40 Hz for the duration of the trial such that on a trial where the red bars were flickered at 30 Hz, the blue bars would be flickered at 40 Hz and vice versa. Each bar was randomly re-plotted on each 83 ms frame. During coherent motion, 32% (low coherence) or 54% (high coherence) of either the red or blue bars were randomly selected on each frame to be displaced in one of 5 possible orientation (15-159° with 36° increments), while the remaining bars were assigned one of 4 other motion directions. Participants were instructed to report the coherent orientation of these flickering bars via a USB compatible 360° flight simulator joystick.

For the calibration block, stimuli consisted of 400 black bars displayed in an annulus like the practice trials but without an attention cue. On each trial, 100% of the bars (i.e., 100% coherence) were formed a coherent orientation in one of the five possible orientations (15-159° with 36° increments). Participants reported the motion direction of coherent orientation using the flight simulator joystick.

Stimuli were presented on a PC running Windows XP using MATLAB (MathWorks, Natick, MA) and the Psychophysics Toolbox (version 3.0.8; (Brainard, 1997; Pelli, 1985)). Participants were seated 60 cm from the CRT monitor running at 100 Hz with a gray background of 42.682.20 cd/m^2.

Procedures

Participants performed an orientation variant of a random-dot motion task (RDMs; Williams & Sekular, 1984; Britten et al., 1993; Churchland, Kiani, & Shadlen, 2008; Forstmann et al., 2010), such that stimulus strength (coherence levels), selective attention, and expectation about target coherent orientations could be manipulated. Participants completed 4 test sessions: each of which consisted of practice trials, calibration trials, and test trials. For 6 locks of test trials, each trial began with a display consisting of a fixation point surrounded by an annulus of flickering randomly oriented red and blue bars. After 400-800 ms, the fixation point was replaced by an attention cue, either red, blue, or green. A red or blue cue informed participants of the color of a forthcoming target coherent orientation such that participants could monitor either the red or blue bars (focused attention). A green cue did not provide information about the color of the target coherent orientation and thus participants had to monitor both red and blue bars for a coherent orientation (divided attention). After 600-1000 ms, the red and blue flickering bars were presented for 800 ms, such that a proportion of either red or blue bars formed a coherent orientation at one of the 5 possible orientations. The remaining bars were randomly assigned to the other 4 directions. Note that the attention cue was always valid such that on focused attention trials, the coherent orientation was represented by red bars on half the trials (red attention cue) and by blue bars (blue attention cue) on half the trials. The target display was followed by a 500-ms of a display of a fixation point surrounded by randomly oriented red and blue bars. Each trial ended with a blank intertrial-interval (ITI) that lasted for 666.7-1000 ms. Participants indicated the target coherent orientation by moving the flight simulator joystick its maximal distance in a direction matching the coherent orientation. After making a response, participants turned the joystick to the center in preparation for the next trial. Responses were considered valid when they occurred in the interval between target onset and ITI offset. Together, this study design allowed us to simultaneously investigate the effects of feature expectation and selective attention on information processing during decision-making.

To familiarize participants with the task and the joystick, practice trials were given at the beginning of each session. There were a total of 120 trials from all coherence levels (high/low coherence level), attention conditions (focused/divided), orientations (15-159° with 36° increments), and target color conditions (red/blue). After training, participants performed a block of calibration trials. The purpose of the calibration trials was to estimate how each participant represented each orientation. These estimates were used to compute performance accuracy on the test trials. Participants reported coherent orientations consisting of 100% coherent bars using the flight simulator joystick. In each session, participants completed one block of 120 trials (24 of each of the 5 possible orientations).

Behavioral Analysis

On each trial, we first identified the final coordinate of the joystick at maximum distance from starting point and used that coordinate to compute the final angle response on each trial (i.e., final response). We then computed an absolute error between this final response and the presented coherent orientation (i.e., final response error) on each trial. Any trials with missed responses and responses that were too early were discarded from further analysis.

We then examined the impact of coherence level (low/high), attention (focused/divided), and expectation (expected /unexpected) on response trajectories and response errors across time. Response trajectory is a measure of a temporal integration of sensory information from the onset of target presentation leading up to a decision choice. Response trajectory was computed as a cumulative distance the joystick was moved from the center across time (Fig. 2, left panel). A response trajectory with a steeper slope represents a faster, more efficient processing of sensory information. In order to examine performance accuracy, we computed response errors by calculating the difference between the presented coherent orientation and the joystick response angle at each time point. This analysis was performed on the behavioral data aligned to the onset of target coherent orientation (Fig. 2, middle panel) as well as on the data aligned to the peak of response trajectories (Fig. 2, right panel).

EEG Recording and Analysis

EEG data were recorded using a 64+8 channel BioSemi Active Two system at a sampling rate of 1024 Hz. Two reference electrodes were placed at the mastoids. We monitored vertical eye movements and blinks via two pairs of electrodes placed above and below the eyes. Horizontal eye movements were monitored via another pair of electrodes placed near the outer canthi of the eyes The EEG data were referenced online to the BioSemi CMS-DRL reference, and all offsets from the reference were maintained <20 uV. The data were preprocessed with a combination of EEGlab 11.03.1b (Delorme and Makeig, 2004) and custom MATLAB scripts.

After data collection, the continuous EEG data were re-referenced off-line to the mean of the left and right mastoid electrodes and applied 0.25 Hz high-pass and 58 Hz low-pass Butterworth filters (third order). An additional 10 Hz low-pass filter was applied before plotting the data, but all reported statistics were performed on the 58 Hz low-pass filtered data (Luck, 2005; for similar methods, see Hickey, Chelazzi and Theeuwes, 2010; Itthipuripat and Serences, 2015). The data were then visualized from each trial and discarded epochs contaminated by residual eye blinks and vertical eye movements (≥ 80-150 μV deviation from 0, with thresholds chosen for each participant), horizontal eye movements (≥ 75-100 μV deviation from 0, with thresholds chosen for each participant), excessive muscle activity, or drifts. This procedure resulted in the rejection of 13.5% of trials on average (1.32% SEM across participants; ranged from 3.2% to 22.1% of trials). Data from two participants were excluded from further analysis due to the rejection rate of more than 30% of trials. Finally, the data were temporally aligned to the onset of a target.

Next, artifact-free EEG epochs were sorted into different experimental conditions based on coherence level of target orientation (high or low), on attention directed to target stimuli (focused or divided), on the flicker frequency of target stimuli (30 Hz or 40 Hz), and on the status of each coherent orientation in the context of a given block (expected or unexpected). Due to the uneven number of expected and unexpected trials, we first performed resampling with replacement on data in each experimental bin (e.g., focused attention and divided attention) such that the size of each bin after resampling was equal to the that of the smallest experimental bin (i.e., unexpected condition). To compute event-related potentials (ERPs), the target-aligned EEG data were averaged for each experimental condition. The ERPs were baseline-corrected from 200 before the onset of an attention cue to the onset of an attention cue.

To compute steady-state visually evoked potentials (SSVEPs), the non-baseline-corrected EEG data from each experimental bin for each participant were used to compute Fourier coefficients at frequencies of 30 and 40 Hz (the two stimulus frequencies). The resulting 30 and 40 Hz SSVEPs were then baseline-corrected across a time window extending 200 ms before their respective time-domain SD (i.e., 30-Hz SSVEP data were baseline-corrected from 262.5 to 62.5 ms before cue onset and 40-Hz SSVEP data were baseline-corrected from 245.9 to 46.9 ms before cue onset). The SSVEPs were then extracted from the central occipital (Oz) electrode where the SSVEP signal peaked across both center frequencies of 30 Hz and 40 Hz. Finally, amplitude of 30 and 40Hz SSVEPs was normalized by its respective maximal amplitude to account for differences across frequency level.

Next, we examined the impact of target coherence, attention directed to target stimuli, and the expectation status of target coherent orientation on the SSVEPs and on four ERP components recording from the centro-parietal (CPz), parietal (Pz), parieto-occipital (POz), and occipital (Oz) electrodes.

Statistical Procedures

Behavioral Analysis

All reported confidence intervals (CIs) were computed by resampling the data with replacement (i.e., bootstrapping) for 1,000 iterations for each bootstrapping procedure. Note that this method constrains the resolution of our p-values to a lower limit of $p \leq 0.001$. We generated permuted null distributions of response trajectories and response errors for each participant, and condition, and for each time point.

For tests comparing a bootstrapped distribution against zero, *p* values were computed by conducting two one-tailed tests against 0 (e.g., mean(difference in response trajectories < 0) and mean(difference in response trajectories > 0) and doubling the smaller *p* value.

EEG Analysis

We examined the impact of coherence level, attention, and expectation on four ERP components: the occipital component recorded from the Oz electrode, the parieto-occipital component recorded from the POz electrode, the parietal component recorded from the Pz electrode, and the centro-parietal component recorded from the CPz electrode. To evaluate the influence of our manipulations on the amplitude of the ERp components, we used 1) three-way repeated-measures ANOVAs with within-subject factors for target coherence (2 levels: low and high coherence), attention (2 levels: focused and divided attention), and expectation status of the target coherent orientation (2 levels: expected and unexpected orientation); and 2) paired t-tests within-manipulation comparisons. These ANOVAs and paired t-tests were performed on the mean ERP amplitudes across consecutive 50 ms windows from 200 ms before to 1000 ms after target onset. Corrections for multiple comparisons were implemented using the false discovery rate (FDR) method (Benjamini and Hochberg, 1995) based on data from all four electrodes of interest.

The same ANOVA analyses and t-tests were then performed on the normalized SSVEP amplitude recorded from the Oz electrode. This electrode was chosen as it displayed maximum response amplitude at 30 Hz and 40 Hz. ANOVAs were performed on the target-aligned SSVEP response across consecutive 50 ms from 1) 500 ms before to target onset to target onset; 2) target onset to 500 ms after target; and 3) 500 ms to 1000 ms after target onset. Corrections for multiple comparison were computed separately for each of these three windows.

Figures

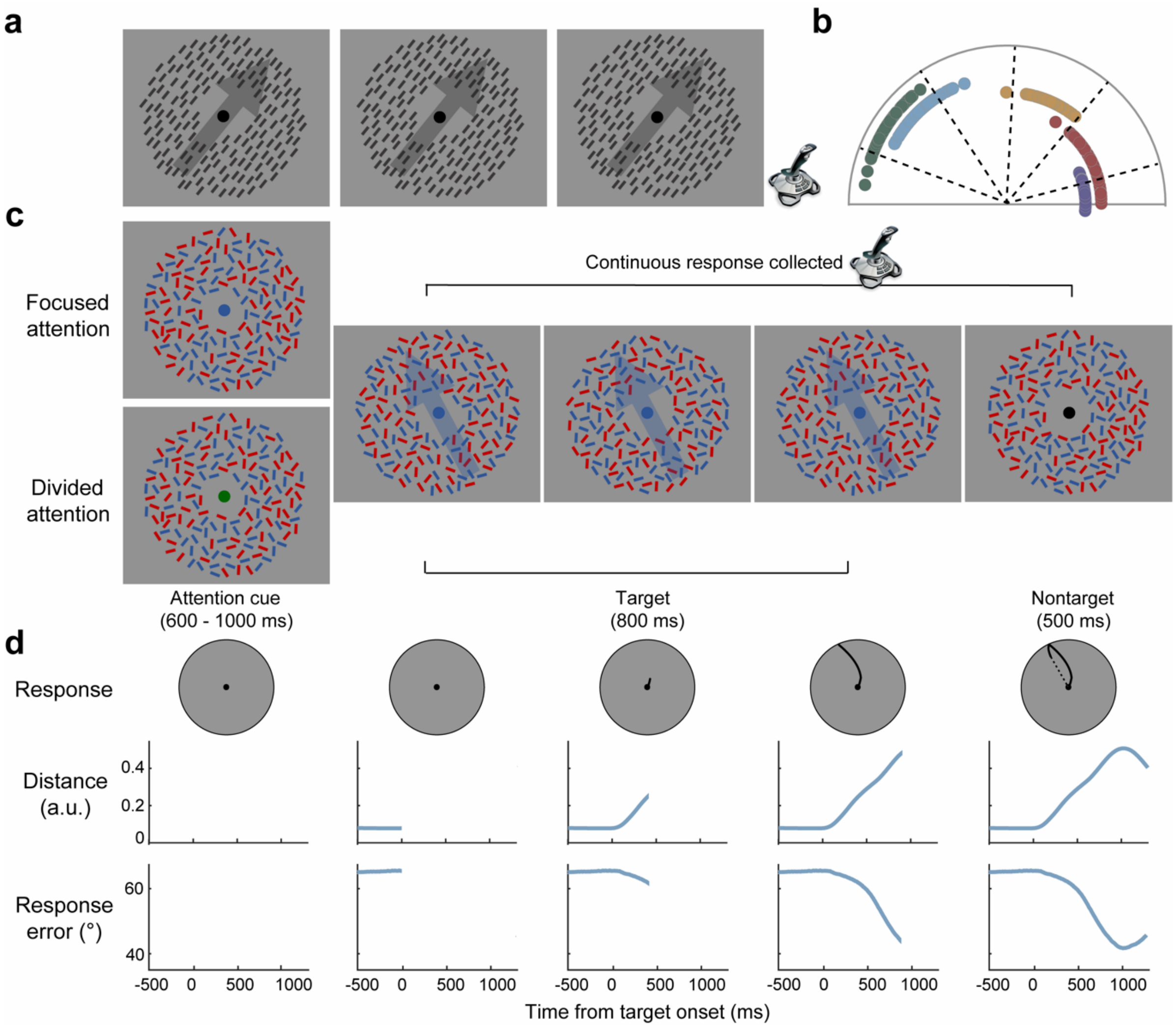


Figure 1 | A Continuous probabilistic decision making task. a. The calibration block. On each trial, participants saw flickering black bars and were instructed to report the coherent orientation of these bars by moving a 360 deg flight simulator joystick. **b.** Stimulus space. There were five possible orientations from xx to xx with xx deg increment (each represented by a dotted line). Solid circles are responses from one sample participant from a calibration block corresponding to each of the five target orientations. **c.** The main experimental task. Each trial began with a fixation point (400 to 800 ms) and was followed by an attention cue (600 to 1000 ms) to indicate the color of the bars that would represent coherent orientation (target). A red (blue) attention cue indicated that coherent orientation would be represented with red (blue) bars (focused attention condition). A green attention cue indicated that coherent orientation would be represented with either red or blue dots, i.e., the participant had to discern which color of bars was in coherent orientation (divided attention). Coherent orientation was presented for 800 ms during which the participant could start beginning to make a response by moving the joystick from the starting point in the directions that match the perceived coherent orientation. Responses were collected until the nontarget presentation which lasted 500 ms.

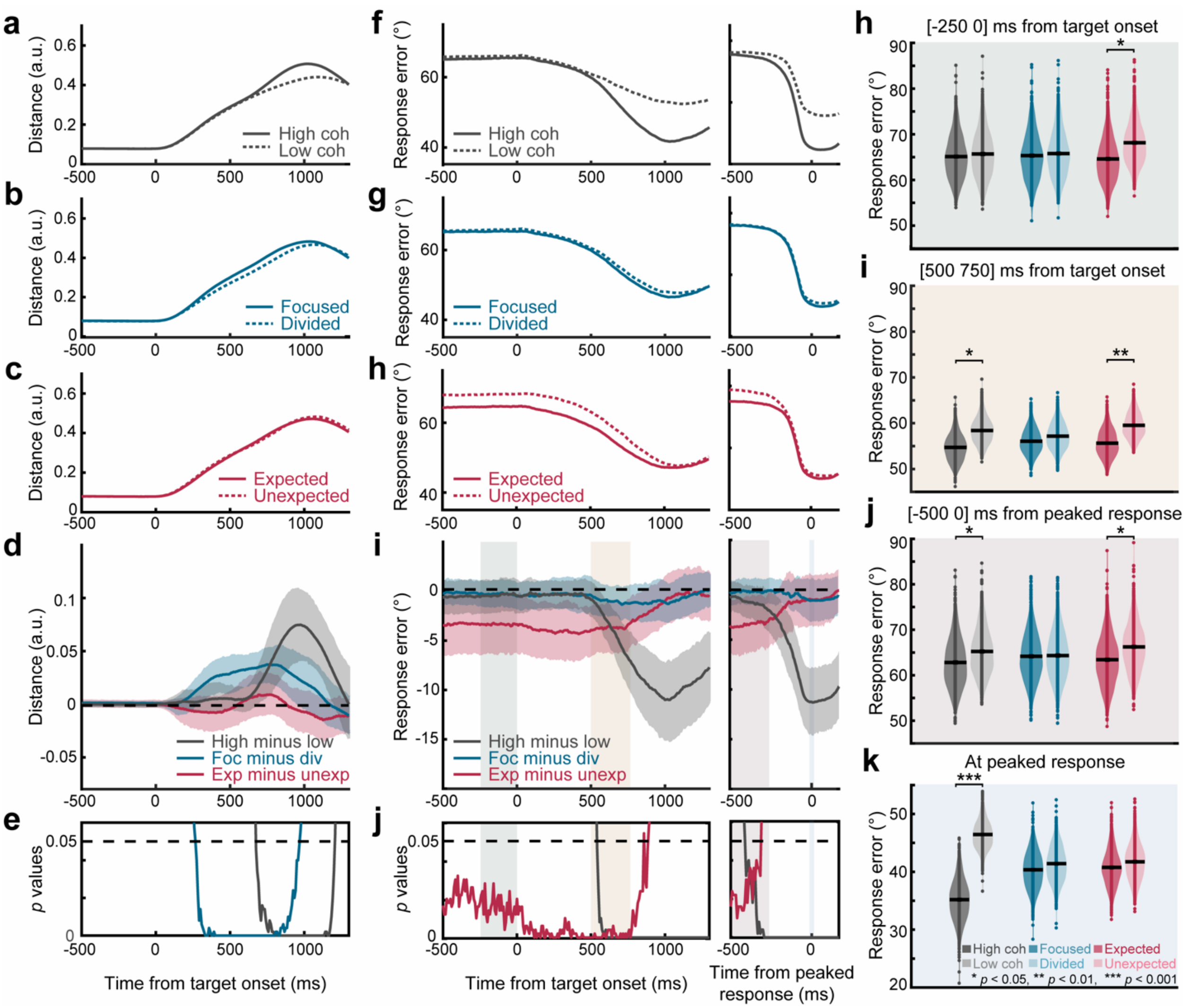


Figure 2 | Differential effects of selective attention and prior expectation on response trajectories and response errors. Target-aligned response trajectories (left) and target-aligned response errors (middle) were plotted from the onset of coherent orientation (0 ms) to 1000 ms after onset. Response-aligned response errors (right) were plotted from 500 ms before target onset to 1250 ms after target onset. Response trajectories and response errors were plotted **a,** as a function of orientation coherence (high/low), **b**, as a function of attention (focused/divided), and **c,** as a function of expectation (expected/unexpected). **d,** Differences in response trajectories and response errors for each manipulation condition were plotted together with the associated *p* values (**e**). The amplitude of response trajectories was higher on trials with high orientation coherence versus trials with low coherence from 675 to 1200 ms after the onset of coherent orientation (resampled $p < 0.05$; **a**). Focused attention led to a greater amplitude of response trajectories in comparison to divided attention from 266.7 to 966.7 ms after target onset (resampled $p < 0.05$; **b**). Response trajectories were not modulated by manipulations of expectation (**c**). Response errors were lower when coherent orientation was presented at a high coherence than at a low level from 541.4 to 1300 ms after target onset and from -225 ms before peaked response to 250 ms after peaked response (resampled $p < 0.05$; **f**). Response errors were lower when attention was focused than when attention was divided from 691.7 to 716.7 ms after target onset (resampled $p < 0.05$; **g**). Expectation reduced baseline response errors (i.e., prior to and at the onset of coherent orientation), and this effect lasted from 500 ms before target onset to 833.3 ms after target onset (resampled $p < 0.05$; **h**). Additionally, response errors were lower on expected trials from 500 ms to 133.3 ms before the peaked responses (resampled $p < 0.05$; **h**). For **e**, the legend is the same as in (**d**). Error bars for each of the three measures indicate 95% CIs computed by resampling the data distribution.

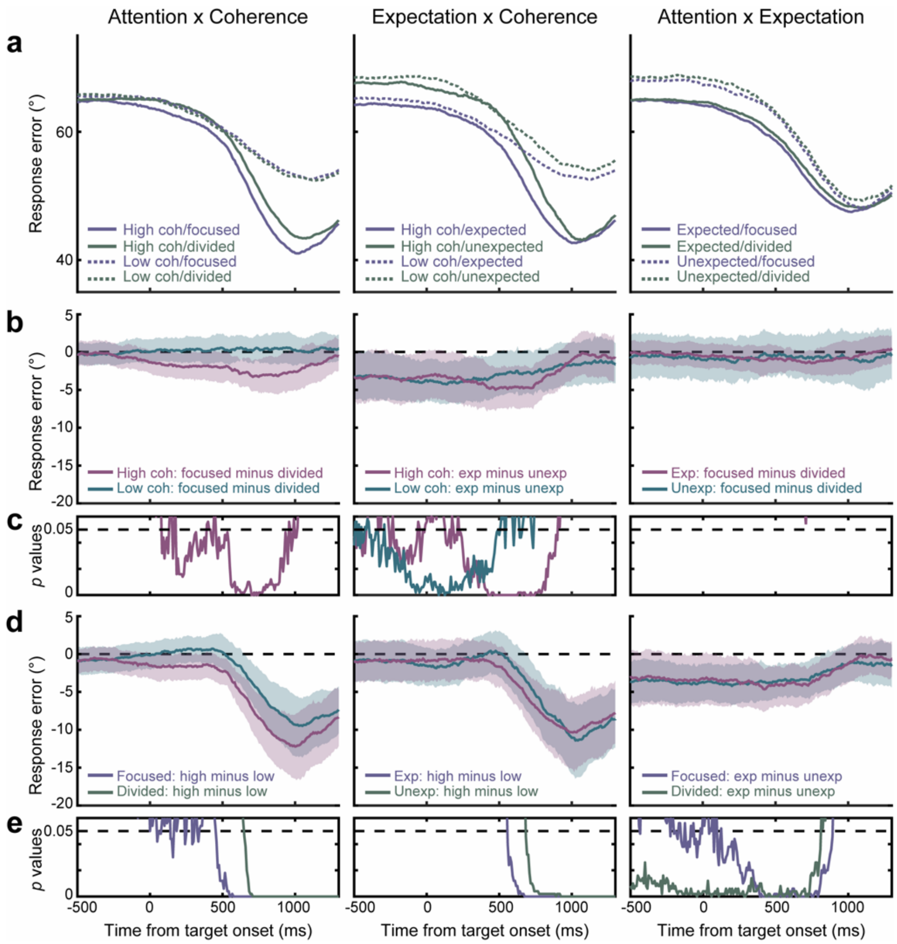


Figure 3 | Intricate interplay of top-down and bottom-up signals underlie successful decisions

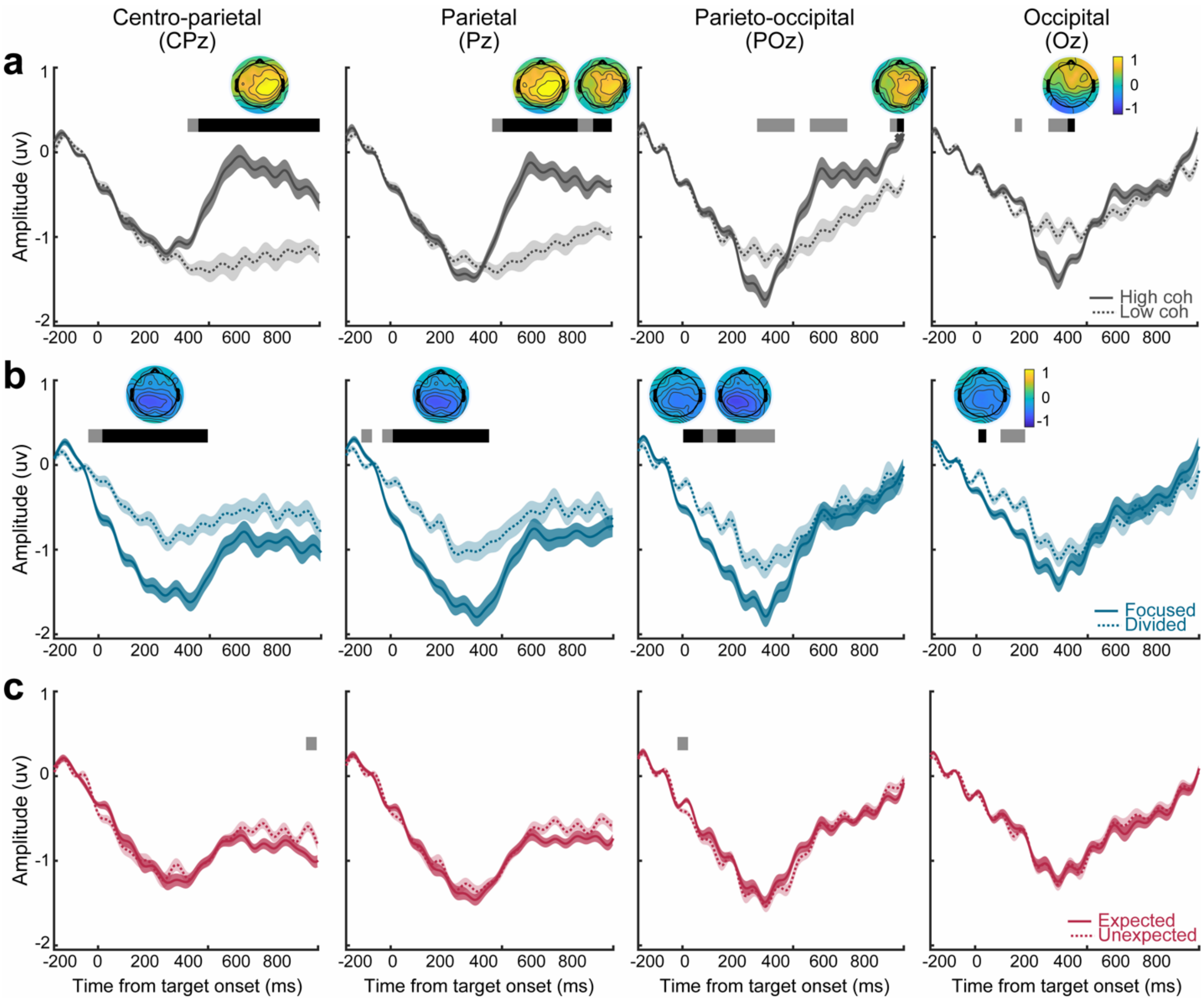


Figure 4 | Event-related potentials (ERPs) as a function of orientation coherence, attention, and expectation. Amplitude of ERPs was computed from all trials of each manipulation condition recorded from centro-parietal (CPz), central (Cz), parieto-occipital (POz), and occipital (Oz) electrode. ERPs are plotted from 200 ms before target onset to 1000 ms after target onset **a**, as a function of orientation coherence (high/low), **b**, as a function of attention (focused/divided), and **c**, as a function of expectation (expected/unexpected). Focused attention induced early changes in the ERP responses across all channels (CPz: target onset to 500 ms after target onset; Cz: target onset to 450 ms after target onset; POz: target onset to 100 ms and 150 to 250 ms after target onset; Oz: target onset to 50 ms after target onset), whereas the effect of orientation coherence occurred later in time (CPz: 450 to 1000 ms; Cz: 500 to 850 ms and 900 to 1000 ms; POz: 950 to 1000 ms; Oz: 400 to 450 ms after target onset). ERP responses were not affected by expectation.

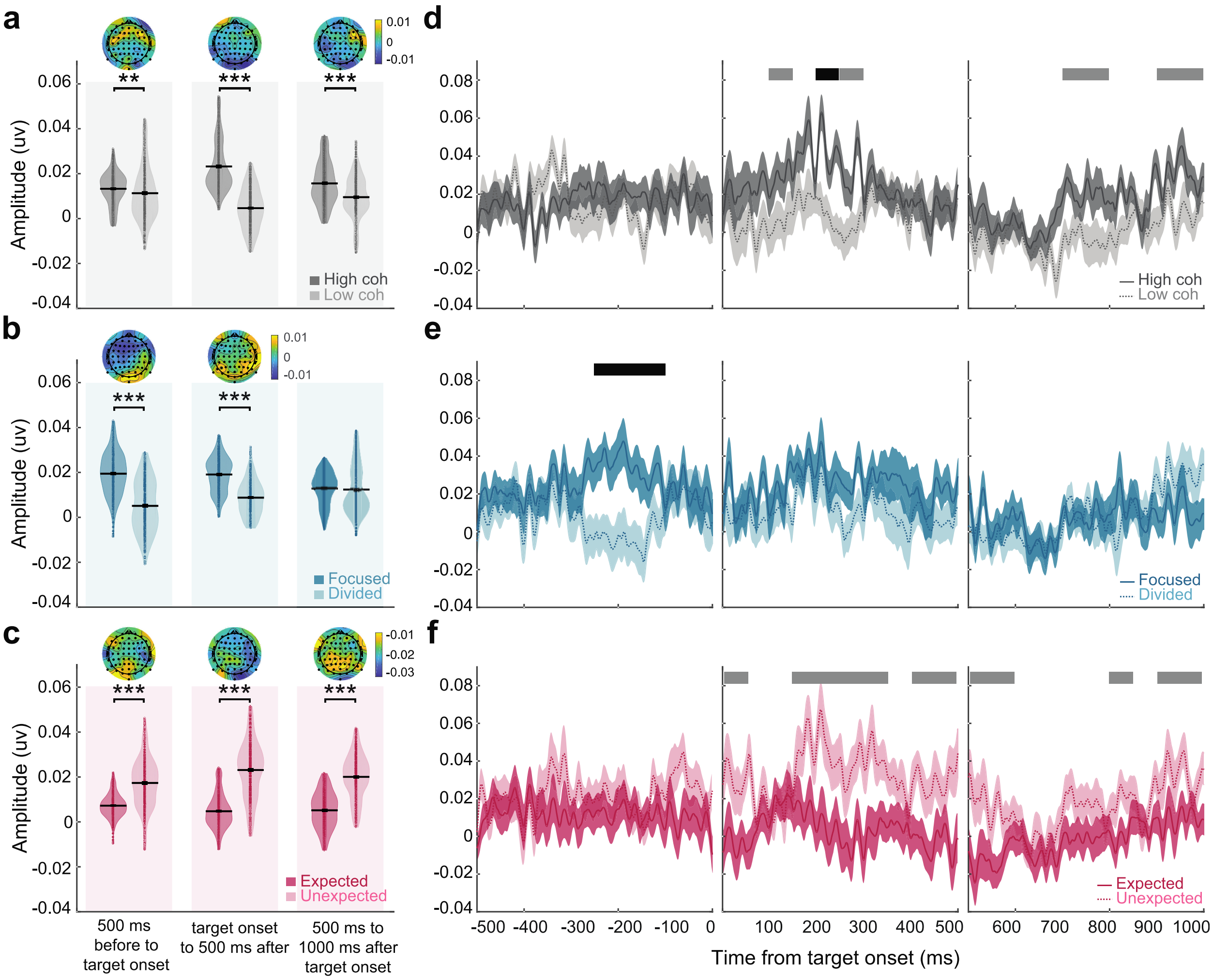
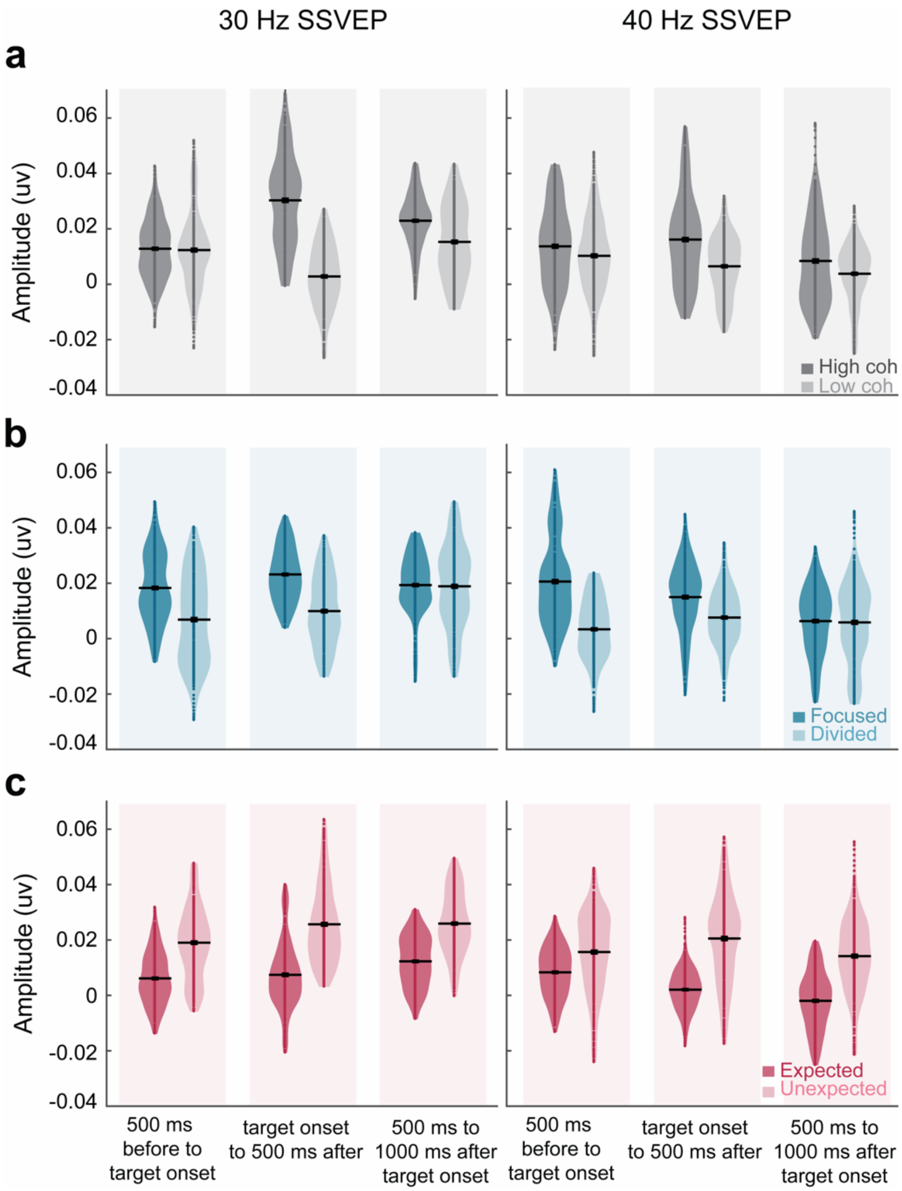


Figure 5 | Steady state visually evoked potentials (SSVEPs) as a function of orientation coherence, attention, and expectation. Normalized amplitude of SSVEPs was computed from all trials of each manipulation condition recorded from Oz electrode. SSVEPs are plotted in three windows: (left), 500 ms before target onset to target onset; (middle), target onset to 500 ms after target onset; and (right), 500 ms to 1000 ms after target onset. SSVEPs are plotted **a**, as a function of orientation coherence (high/low), **b**, as a function of attention (focused/divided), and **c**, as a function of expectation (expected/unexpected). Focused attention led to higher SSVEP amplitude from 250 ms to 50 ms before the onset of coherent orientation. High orientation coherence increased SSVEP amplitude from 200 ms to 250 ms after target onset. Expectation had no effects on SSVEP responses.



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