Automatic detection of orientation variance

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Rapid extraction of the overall statistics of the visual scene is crucial for the human ability to rapidly perceive the general ‘gist’. The aim of this work was to investigate if there exists neural evidence for such a process i.e. automatic, unattended detection of overall statistical differences between scenes. In order to do this, Visual Mismatch Negativity (vMMN), an early evoked neural response component, was measured. We presented a sequence of sets of oriented patterns of a given (random) mean orientation and varied the variance of the orientations of the patterns, so that some sets contained similar orientations (ordered) or the orientations were random (disordered). These two types of sets of patterns were presented in an oddball sequence such that one type occurred often and the other was a rare, unexpected stimulus. We found a significant vMMN in response to a randomly oriented stimulus amongst more ordered stimuli, which suggested that humans perceive ‘ordered’ vs ‘disordered’ scenes categorically. We conclude that by manipulating the variance of the orientations contained within each stimulus we are able to show that this property is automatically encoded in visual neural response.

1. Background

Visual Mismatch Negativity (vMMN), an early evoked neural response component, is elicited automatically (i.e. even when the stimuli are unattended) when an ‘unexpected’ (termed ‘deviant’) visual stimulus appears amongst a series of expected (termed ’standard’) stimuli – this kind of sequence is termed an oddball paradigm. VMMN has been suggested to reflect automatic pattern detection over a sequence and may reflect the processing of categories[1]. Recent research has suggested that we are able to rapidly extract overall scene meaning (referred to as ‘gist’) in a first-pass analysis that is not reliant on detailed analysis of individual parts of the image. It has been suggested that the way we are able to process the gist of a scene rapidly is via the use of summary scene statistics, such as average properties and the variance of properties in the scene[2,3]. Suggested properties that may vary in their statistics across natural scenes are spatial frequency content and orientation distributions [3]. This rapid extraction of global properties suggests that they may be encoded automatically, but so far no neural evidence for this exists. More recent work based on a review of behavioural evidence has suggested that these ensemble statistics are used by the visual system to test hypotheses about whether the distribution of features of different scenes differ [4]. A further recent behavioural study demonstrates how the learning of ensemble statistics develops over time [5].

We examined whether vMMN would be sensitive to orientation scene statistics (even whilst not attending to the presented scene). This signature would show a detection of a difference in orientation variance, thus demonstrating quick automatic initial extraction of this property. vMMN has been shown to be a marker of rapid learning of stimulus properties, but it is not known if it is sensitive to differences in the distributions of visual features within scenes. We test whether the orientation variance of scenes is a stimulus category that can be learnt in order to build up an expectation - and hence detect deviations from the expected stimulus. By using vMMN we can measure neural responses when the detection of the scene statistics is not task relevant and hence find a neural correlate for this automatic encoding, mapping on to behavioural results.

We presented a set of oriented Gabor patterns of a mean orientation randomly chosen for each stimulus in a sequence, and varied the width of the standard deviation of the orientations of the patches within stimuli, so that some sets had more similar orientations within them (ordered) or the orientations contained in the set were random (disordered). The orientations were drawn from a Gaussian distribution, so we can also think of variance as orientation entropy, which is directly related to the log of the standard deviation (s.d.). As the orientations and positions of the Gabor patterns were also chosen randomly for each stimulus, there should be no localized adaptation to a specific orientation. In order to examine the automacity of the encoding we also had a central task that required continuous monitoring of a moving dot and keeping it within a box using a joystick – thus rendering the stimulus changes outside the window of attention. See Figure 1. Each of the three standard deviation conditions were paired in an oddball paradigm, each playing the role of deviant in one condition and standard in the reverse condition. When calculating vMMN we only compared responses to the same stimulus, contrasting the response to when it appeared frequently (standard) to when it appeared rarely (deviant). In an additional condition we interleaved a random mixture of orientation variances to check how this fundamental property alters the ERP waveform per se and to ascertain the role of prediction in any vMMN observed, as in this case no prediction should occur, as all orientation variances are equally likely [9].



Figure 1. The three types of stimuli used in our main oddball conditions. The numbers indicate the standard deviation (s.d.) of the distribution the orientations are drawn from. The ones drawn from a 90° s.d. distribution are in effect random orientations, 16° and 4° s.d. produce more ordered patterns (the mean orientation shown here for both is 75°). The mean orientation was randomly selected on each trial, only the variance was manipulated to form standard and deviant stimuli.



Figure 2. A schematic illustration of the oddball sequence in which the 4° s.d. stimuli were the standard stimuli and the 90° s.d. stimuli were the deviant stimuli. The locations of the Gabor patterns varied randomly as did the mean orientation on each presentation, only the s.d. of the orientations was varied systematically to create standard and deviant stimuli.

1. Methods

*Participants*

Fifteen volunteers (eight women; mean age: 22.9; s.d.=2.4 years) with no pre-existing neurological conditions and normal or corrected to normal vision participated in the study for monetary compensation. The number of participants was based on previous studies that measure the well-established vMMN component. Written consent was obtained from all participants prior to the experimental procedure. The study was conducted in accordance with the Declaration of Helsinki, and approved by the Committee of Ethics of the Psychology Institutes in Hungary.

*Electroencephalographic (EEG) recording and analysis*

Electroencephalographic activity was recorded from 61 locations (Ag/AgCl electrodes, EasyCap, Synamps2 amplifier, NeuroScan recording system) according to the extended 10-20 system (DC-100 Hz, 500 Hz sampling rate). The online reference electrode was on the nose tip; ground electrode was attached to the forehead. The horizontal EOG was recorded with a bipolar configuration between electrodes positioned lateral to the outer canthi of the two eyes. The impedance of the electrodes was kept below 10 kΩ. The activity was re-referenced offline to the average electrode activity. The EEG signal was bandpass filtered off-line (0.1-30Hz cut off frequency). The EEGlab [6] Matlab [7] based software package was used for the ERP analysis.

Epochs of 500ms, starting from 100ms before the stimulus onset, were averaged separately for the standard, deviant and control stimuli. Trials with an amplitude change exceeding +/- 100 uV on any channel were rejected from further analysis.

Event related potentials (ERPs) for deviants were calculated from the average of 114 epochs, ERPs for standards were calculated from the average of 472 epochs (standards that appeared immediately after a deviant were not used).

We predefined our electrodes of interest as electrodes Oz and POz, which should serve as a good representations of the posterior activity. Because vMMN is a well-established phenomenon we were also able to pre-define a time interval of interest between 150ms and 250ms after stimulus onset. We used these predefined electrodes and time interval as the comparison in the control condition. We conducted statistics (see below) on the ERP amplitude averaged over this time period.

*Stimulus presentation and design*

Stimuli were presented on a linearized CRT monitor of 1024x768 resolution, with a refresh rate of 75 Hz. Participants were seated at 110cm distance. Stimuli were created in Matlab [7] using the Cogent 2000 package (developed by the Cogent 2000 team at the FIL and the ICN) and Cogent Graphics (developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience). Background luminance was 36cd/m2 mid-gray.

In the EEG recording session there were 6 oddball sequences with 90°/16, 90°/4° and 4°/16° s.d. paired, with each taking the role of standard (frequent) in one sequence and deviant (infrequent) in another. See Figure 2 for an illustration of the 90°/4° oddball sequence with the 90°s.d. stimuli forming the deviant stimuli and 4° s.d. stimuli playing the role of standards. 16.5% of the stimuli were deviants, with 3-7 standards in between (the number in between varied randomly). In the equal probability control condition 0°, 4°, 8°, 16°, 24° and 90° s.d. appeared randomly interleaved, with each s.d. appearing an equal proportion of times, 16.5%.

Each one of the 7 (6 oddball, 1 control) conditions was repeated over two runs, with the first run of each example appearing in the first half of the experiment, and the second run in the second half of the experiment, but within the halves of the experiment runs were randomly ordered. This meant we could keep runs to about 5 minutes long.

The orientations and positions of the Gabor patterns were chosen randomly on each trial, avoiding repetition. Mean orientation was randomly chosen from [15° 45° 75° 105° 135° 165°] and for each mean orientation there were 5 versions with different random positions for the Gabor patches. This means one category of stimulus (i.e. one orientation s.d. value) was represented by 6 x 5 = 30 different images within a run. On each run new images were generated.

Each stimulus consisted of 50 Gabor patches within a rectangle that was 80% size of the screen in the same proportions. The Gaussian envelope of the Gabor patches had full width at half height of 2.45° of visual angle and the carrier sine wave had spatial frequency of 1 cycle/° visual angle. Gabor patches were presented at a 100% contrast (max. luminance 65 cd/m2, min. luminance 0 cd/m2). Each stimulus was shown for 120ms and ISI varied from 440ms to 600ms.

During the EEG recording participants used a joystick to manipulate a dot horizontally that responded to the input with some spatial noise jitter keeping it moving constantly. The task was to keep the ball within the box. The box was approx. 8° of visual angle across, but the dot only slightly jittered its position so that large eye movements were minimized. Our exclusion of epochs with large amplitude changes would rule out large eye movements. We checked that there was no difference in eye movements between conditions. Participants were given feedback at the end of each run.

In the discrimination task after the EEG recording all s.d. examples used in the control condition were shown in sequential pairs, in two intervals, each pairing 20 times in random order, participants were asked to respond which was “more ordered” using a button press. Stimuli were shown for 120ms (same as in EEG part) with an ISI of 520ms.

After the EEG recording participants were asked what they had noticed about the flashing background stimulus. They were classed as “noticed” if they mentioned anything about the direction/orderliness of the stimulus, otherwise they were classed as “not noticed”.

*Statistical analysis*

We tested for the difference in evoked response potential (ERP) for each stimulus between when it was a deviant or a standard using three different repeated measures 2x2x2 ANOVA, in which the independent variables were frequency of occurrence, i.e. standard or deviant, electrode, i.e. Oz or POz and which other stimulus it was paired with. The dependent variable was always the response i.e. average amplitude between 150ms and 250ms after stimulus onset. We also ran two 2x2 ANOVA to test the differences in response to the 90° s.d. (random) stimulus in the oddball and the equiprobable conditions. In the first ANOVA the response to the deviant 90° s.d. (random) stimulus (when paired with the 4° s.d. stimulus) was compared to the response the 90° s.d. (random) stimulus in the equiprobable condition and the independent variables were sequence condition (oddball or equiprobable) and electrode (Oz or POz). In the second ANOVA the response to the standard 90° s.d. (random) stimulus (when paired with the 4° s.d. stimulus) was compared to the response the 90° s.d. (random) stimulus in the equiprobable condition with same independent variables. The statictics were calculated using IBM SPSS statistics [8].

1. Results

Each stimulus type in Figure 1 was presented in four oddball paradigms, paired with one of the other two stimuli and taking the role of standard or deviant (example shown in Figure 2). We tested for the difference in evoked response potential (ERP) for each stimulus between when it was a deviant or a standard, across the two comparison oddball conditions it was in and the two electrodes of interest (Oz, POz) using a repeated measures 2x2x2 ANOVA. The responses to the 90° s.d. pattern (random orientations) are show in Figure 3. We find no significant main effect of whether the stimulus was standard or deviant, but do find a significant interaction between whether the stimulus was standard or deviant and which oddball pairing it was in (F1,14=2.64, p=0.03, partial η2 = 0.29). Post-hoc simple effects comparisons reveal that the interaction is driven by a significant difference between standard and deviant when the 90° s.d. pattern is paired with the 4° s.d. pattern (mean difference deviant – standard = -0.61, p=0.016, Bonferroni corrections applied, partial η2 = 0.35). In other words we measured a vMMN only when the random stimulus was presented alongside the most ordered stimulus. We obtained no vMMN to the 4°s.d. or the 16° s.d. stimuli paired with either pattern (p>0.1 for all).



Figure 3. Event-related potential (ERP) responses to the 90° s.d. stimuli amongst 4° and 16° s.d. stimuli. The dotted line boxes show the times and electrodes used to calculate the vMMN. N=15 participants. Only when in an oddball sequence with the 4° s.d. stimuli does a difference between standard and deviant emerge.



Figure 4. Responses to each of the patterns in the random control condition. The dotted line boxes show the times and electrodes used to calculate the comparison across responses. N=15 participants.

In the equiprobable control[9] condition we found an interesting pattern across all the different levels of order, shown in Figure 4. Contrasting over the same time window using a two-way repeated measures ANOVA (electrode x s.d. of pattern) we found a near-significant effect of orientation variance (F2.604,45.695=2.976 , Greenhouse-Geisser corrected, p=0.05). Relative to the more ordered stimuli the random stimulus appears to take on the role as deviant. Indeed in the control-deviant comparison usually run to check the effect of predictability, between the response to 90° s.d stimulus in the control condition and when it played the role of deviant paired with 4° s.d. standards, there is no significant difference (2x2 repeated measures ANOVA, 2 electrodes POz and Oz, 2 sequences: F1,14=0.10, p=0.76, partial η2 = 0.07) whereas when we compare the response to the 90° s.d stimulus in the control condition and when it played the role of standard paired with 4° s.d. deviants, we find a similar difference as for the vMMN above – the control stimulus response looks like a deviant response, as if the more ordered stimuli have grouped together to form standard stimuli (mean difference deviant – standard = -0.55, F1,14=16.1, p=0.001, partial η2 = 0.53). Again, here we are comparing the response to the same stimulus – only its context is changed.

In the behavioural task on all comparisons between the two levels of orientation variance, participants were above chance on average in choosing which one was “more ordered”, showing that they were able to detect the differences in the standard deviations of the orientations. When participants were asked what they had noticed about the background patterns, six participants were classed as having noticed something about their orderliness.

1. Discussion

We found a significant vMMN was elicited in the response to a stimulus consisting of random orientations amongst a stimulus in which all the orientations were similar to each other. This result suggests that people are able to automatically detect a rare disordered stimulus amongst frequent highly ordered stimuli even when attention is directed elsewhere, by showing a neural marker of this difference. It seems that the statistics of the stimulus (in this case the orientation variance) build up an expectation. However we did not find vMMN in response to the ordered stimulus, suggesting that when totally randomly oriented stimuli are shown repeatedly, no expectation is built up – we suggest that this is because there is no pattern in this case for the visual system to extract. Similar results have been found in studies where expectation effects in the form of vMNN were found for rare random noise patterns amongst symmetric patterns, but not vice-versa [10]. Importantly none of the difference in response to disordered stimuli can be in this case due to local orientation adaptation effects as stimuli vary randomly in orientation and location, so expectation must be built up on rapid extraction of the variance of the orientations. However we also found no vMMN when the random stimulus was paired with a less highly ordered stimulus, showing that the orientation variance difference needed to be sufficiently large to be detected. In the control condition where we showed stimuli containing many levels or orientation variance an equal amount of times, in random order, we found that the earliest onset visual responses are the same on average to all stimuli regardless of orientation variance. We found a near significant difference emerge between the different levels of variance at around 150-250ms. In particular we found a significant difference between the response to the random stimulus in the control condition and when it played the role of standard in between highly ordered stimuli, this difference taking on a similar pattern to the vMMN observed for the random stimulus. This suggested that the disordered stimulus behaved as a deviant amongst the more ordered stimuli in the control condition.

Parkes et al. [11] have previously shown that humans pre-consciously pool signals to extract the mean. Solomon[12] showed that variance discrimination can be carried out efficiently under fully attended conditions. This work shows that changes in variance can be automatically detected outside the locus of attention and provides neural evidence for early processing of this property in the visual cortex, therefore supporting behavioural evidence that this statistic could plausibly used in calculations for rapid scene recognition.

This is important as natural scenes have been shown to vary in the distribution of orientation information[3]. This rapid extraction of orientation statistics may form the basis of our ability to rapidly discriminate such scenes [13]. The variance of incoming information is also important as it has been shown that estimates of the noise of a signal (i.e. how reliable an estimate of the mean is given by a signal) are used to calculate the weighting of a signal when combining it with other cues [14]. As such, extracting orientation variance early and automatically may be one of the fundamental processes necessary for cue combination as well as scene recognition.

We show for the first time that the variance of the orientations of the scene is automatically extracted, providing neural evidence, and as such is a basic feature that we can use to form categories of ‘ordered’ and ‘disordered’ stimuli. This provides a plausible mechanism in the form of vMMN that allows us to rapidly distinguish natural scene categories that differ in their orientation distributions, allowing us to perform ‘gist perception’.

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**Data Availability**

Raw data with stimulus timings: http://doi.org/10.5281/zenodo.581188

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