Symmetry perception and affective responses: A combined EEG/EMG study

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ABSTRACT

The perception and appreciation of visual symmetry have been studied in several recent EEG experiments. Although symmetry is known to be an important determinant of aesthetic preference, previous studies have concluded that evaluation does not occur spontaneously. These studies also found that symmetrical and random patterns do not differ in terms of early sensory processing, within 200 ms of stimulus onset. We presented participants with symmetrical or random abstract patterns, which they had to classify correctly. Contrary to previous work, we found that N1 amplitude was sensitive to all types of regularity, and P1 was sensitive to rotational symmetry. We also found that activity in the Zygomaticus Major, the facial muscle responsible for smiling, was greater for reflection patterns. However, we were able to reverse this effect by changing the task so that participants had to treat random patterns as the *target stimuli*. We conclude that participants spontaneously select reflectional symmetry as the target, and positive affective responses automatically follow from successful target detection. This work provides a new account of the neural mechanisms involved in visual symmetry perception.

1. Introduction

A lot is known about visual symmetry perception (Treder, 2010, Tyler, 1995, Wagemans, 1995). Reflectional symmetry is detected more quickly than other regularities, such as rotation or translation (Palmer & Hemenway, 1978, Royer, 1981), particularly when the axis of reflection is vertical (Friedenberg & Bertamini, 2000; Mach, 1886; although see Wenderoth, 1994). While V1 may code information about axis orientation (van der Zwan, Leo, Joung, Latimer, & Wenderoth, 1998), neuroimaging studies have found symmetry-related activations in extrastriate visual areas such as V3a, V4, V7 and the lateral occipital complex (LOC), but not in V1 or V2 (Chen, Kao, & Tyler, 2007; Tyler et al., 2005, Sasaki, Vanduffel, Knutsen, Tyler, & Tootell 2005).

Symmetry perception holds a particular fascination because symmetry is so closely related to beauty. Indeed, the physicist Herman Weyl claimed that "beauty is bound up with symmetry" on the first page of his classic book (Weyl, 1953), and visual balance has been considered an essential aspect of classical artworks (Arnheim, 1974). Meanwhile, Ramachandran and Hirstein (1999) considered preference for symmetry to be one of their eight laws of aesthetic experience. Anatomical symmetry could be an indicator of reproductive fitness (Møller, 1992),

perhaps explaining why symmetrical faces are perceived as more attractive (Cárdenas & Harris, 2006). In line with these considerations, many empirical studies have found symmetry to be the best predictor of preference for abstract, geometrical patterns (Eisenman, 1967; Eysenk, 1941; Jacobsen & Höfel, 2002).

The perception and evaluation of symmetry have been explored in a series of recent electroencephalography (EEG) studies. Jacobsen and Höfel (2003) presented symmetrical or random patterns. In half the trials, participants were asked to categorize the patterns as symmetrical or random (descriptive judgment), while in the other half, they were asked to categorize the patterns as beautiful or ugly (evaluative judgment). Their analysis focused on three ERP components. (1) The *sustained posterior negativity* (600–1100 ms post stimulus): In occipital electrodes, amplitude was more negative in symmetrical than random trials (2) The *frontocentral negativity* (300 to 400 ms), which was larger for ugly patterns in the evaluation task. (3) The *late positive potential* (440 to 880 ms) which occurred in central/parietal electrodes, and which was more right lateralized in the evaluation task. Amongst other things, the results implied that evaluation does *not* occur spontaneously during the description task, because evaluation-related components, such as the frontocentral negativity, were absent.

This conclusion was tested directly by Höfel and Jacobsen (2007a). Symmetrical and random patterns were presented and participants were instructed to either observe the patterns, or to contemplate them aesthetically. In both conditions, the

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symmetry-related sustained posterior negativity was evident. However, the right lateralization of the late positive potential was only present in the contemplation condition, while the frontocentral negativity (previously associated with 'ugly' judgments) was completely absent in this experiment. The results suggested that aesthetic processing "appears to require intention and is not spontaneous in character" (*p*. 30). More recently, the same conclusion was reached in two studies on facial beauty (Roye, Höfel, & Jacobsen, 2008; Schacht, Werheid, & Sommer, 2008).

Despite these important findings, the above studies cannot rule out the possibility that other psychophysiological measures might be sensitive to spontaneous evaluation. In our study we attempted to detect spontaneous evaluation of symmetry using facial electromyography (EMG) while recording ERPs from the scalp. In previous work, activation of the smiling muscle (the Zygomaticus Major, ZM) has been used to measure positive emotional responses (Achaibou, Pourtois, Schwartz, & Vuilleumier, 2008). Moreover, ZM is activated by stimuli that are processed *fluently*, such as prototypes, or objects with high sensory motor compatibility (Cannon, Hayes, & Tipper, 2010; Winkielman & Cacioppo, 2001; Winkielman, Halberstadt,

Fig. 1. Trial structure in Experiment 1. All trials began with a 1.5 s fixation baseline, then either a reflection or random pattern. The reflection patterns had two-fold symmetry. Random patterns are based on the same positional template, but size and orientation of the elements were unconstrained across the quadrants. In Experiment 1A, 12 participants pressed one button for reflection and another button for random. In Experiment 1B, 12 more participants saw the same response screen, but the word 'reflection' was replaced with the word 'symmetry'. The position of words on the response screen indicated whether to press the left or right button to enter a particular response. Positioning was reversed in half the trials.

Fazendeiro, & Catty, 2006). Given these findings, it is possible that symmetry will also produce an automatic affective response, manifesting in activation of the ZM muscle.

The stimuli used in our study were patterns created with a symmetrical positioning of black and white elements (Fig. 1). For the regular patterns, the size and orientation of the elements were fixed across the quadrants, giving two-fold symmetry. For the random patterns, size and orientation of the elements varied between quadrants. The density, numerosity, and contrast of the patterns, as well as the average distribution of luminance were balanced across all conditions. Any differential responses could not be attributed to these factors. This is best appreciated by noting that information from within each quadrant would not be sufficient to discriminate regular and random patterns; the difference was entirely in the relationship between the quadrants. Finally, a novel pattern was generated on every new trial, so that the same pattern was never seen more than once. This is important because exposure is known to be a factor in preference formation and affect (Bornstein, 1989).

An important aspect of the study of symmetry is that it is possible to compare patterns with identical mathematical regularity, but different apparent regularity for the human visual system (Bertamini, Friedenberg, & Argyle, 2002; Mach, 1886; Makin, Pecchinenda, & Bertamini, 2012a, Wagemans, Vangool, Swinnen, & Vanhorebeek, 1993). Unlike previous neuroimaging work (Jacobsen & Höfel, 2003; Höfel & Jacobsen, 2007a,b; Tyler et al., 2005; Sasaki et al., 2005; Chen et al., 2007), we compared electrophysiological responses for reflectional symmetry, where the regularity is perceptually salient, and rotational symmetry, where regularity is less salient. To our knowledge, this is the first study to systematically investigate the neural correlates of the perceptual difference between reflectional and rotational symmetry.

2. Experiment 1

In Experiment 1, we presented participants with two types of stimuli: black and white abstract patterns with two-fold reflectional symmetry, or equivalent random patterns (Fig. 1). The stimuli were similar to those used in previous work (e.g., Jacobsen & Höfel, 2003)[1]. The patterns were on the screen for 3 s, after which participants pressed one button if they had seen a reflection pattern and another for a random pattern. We simultaneously recorded EEG from the scalp and EMG from muscles on the face, most importantly from the left Zygomaticus Major (ZM). We expected ZM activation to be higher for the reflection patterns. We also recorded from the left Corrugator Supercilii (CS, frowning muscle), in order to establish that ZM effects were specific to that muscle (e.g., Winkielman et al., 2006).

There were two parts to Experiment 1. In Experiment 1A, the regular patterns were labelled 'reflection'. In Experiment 1B, they were labelled 'symmetry' (Fig. 1 and Table 1). This manipulation tested the possibility that ZM effects were sensitive to category labels.

The analysis of the EEG data focused on four questions. First, we wanted to replicate the effects reported by Jacobsen and Höfel (2003) and Höfel and Jacobsen (2007a,b), and see if symmetry-related ERPs were systematically related to EMG responses. Second, we used source localization techniques to test whether the extrastriate visual regions identified with fMRI (Sasaki et al., 2005) generated these ERPs. Third, we were curious about the absence of visual evoked potential (VEP) modulations reported in previous EEG work. Treder (2010) argued that this could be attributed to the fact
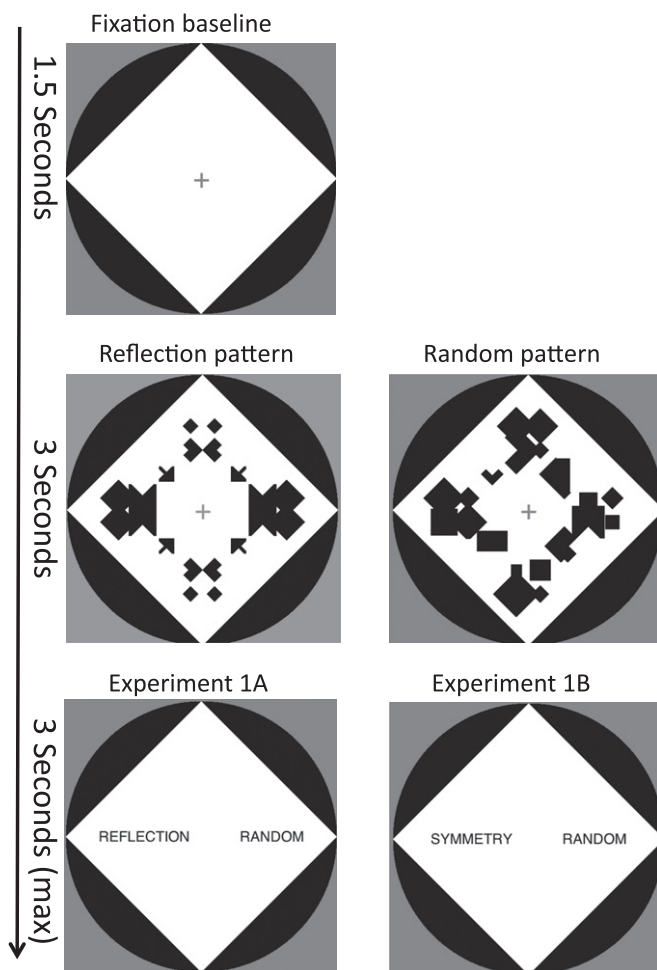
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[1] We thank Professor Jacobsen for sending us examples of his stimuli, although in the end, we chose to generate our own patterns rather than use the images he provided.

Table 1
List of experiments, stimuli and response protocols.

Experiment	Version	Stimuli 1	Stimuli 2	Response button labels	Response to regular	Response to random	N
1	A	Reflection	Random	Reflection or random	Reflection	Random	12
1	B	Reflection	Random	Symmetry or random	Symmetry	Random	12
2	A	Reflection	Random	Yes or No	Yes	No	12
2	B	Reflection	Random	Yes or No	No	Yes	12
3		Rotation	Random	Symmetry or random	Symmetry	Random	12

that symmetry detection occurs late in the visual pathways. However, in previous studies the pattern elements appeared concurrently with a white surrounding square, and this might have dominated the VEP. In order to unmask symmetry-related VEP alterations, the surrounding square was already present at stimulus onset in the current study. Finally, we were interested in the role of oscillatory activity in symmetry perception, which has previously been neglected. Event-related synchronization (ERS) in the upper alpha frequency band ($\sim$12 Hz) may be produced by top-down inhibition, while event-related desynchronization (ERD) could reflect disinhibition, or cortical excitation (Klimesch, Sauseng, & Hanslmayr, 2007). We hypothesized that the onset of all patterns would be accompanied with ERD, and that this would be more pronounced for symmetrical patterns, which are known to produce widespread visual activation (Sasaki et al., 2005).

2.1. Experiment 1 method

2.1.1. Participants
Twenty-four participants (age 18 to 41, 8 male, 0 left-handed) took part, with 12 in Experiments 1A, and 12 in 1B. They were reimbursed for their time. All had normal or corrected-to normal vision and were naïve with respect to the hypotheses of the study. The study had approval from the local ethics committee.

2.1.2. Apparatus
EEG and EMG activity was recorded using a BioSemi Active-Two amplifier in an electrically shielded room. Stimuli were generated and presented on a CRT monitor using *psychopy* software (Peirce, 2007). Participants sat 140 cm from the monitor, with no head constraint or chin rest (as this may have altered facial muscle responses). They entered their responses with the 'A' and 'L' buttons of a computer keyboard. EEG data sampled continuously at 512 Hz from 64 scalp electrodes that were embedded in an elasticised cap and arranged according to the international 10–20 system. Two additional electrodes, called *common mode sense* (CMS) and *driven right leg* (DRL) were used as reference and ground, respectively. Two facial electrodes were positioned over the left smiling muscle (Zygomaticus Major, ZM) and two were positioned over the left frowning muscle (Corrugator Supercilii, CS) muscle. The arrangement of facial electrodes followed standard guidelines (Fridlund & Cacioppo, 1986). Horizontal and vertical electrooculograms were recorded to detect eye movements and blinks in each condition. VEOG and HEOG electrodes were positioned above and below the right eye, and on the outer canthi of both eyes, respectively. Facial muscle and EOG activity was recorded using the external channels of the BioSemi system and also sampled at 512 Hz.

2.1.3. Design
Experiment 1 involved a single within-subjects factor [shape, (reflection, random)] with 80 trials of each condition. Reflection and random patterns were presented in a novel, randomized sequence for each participant. For some analysis, Experiment version (1A, 1B) was included as between-subjects factor.

2.1.4. Stimuli
Stimuli were black and white patterns. In each quadrant, there were nine square elements, four of which were black and five were white. The size of the elements varied between 0.25° and 1° of visual angle, and the orientation was either 45° or 90°. The position nearest the central fixation cross was always white, so the fixation cross was never occluded. The background was a black circle and a white diamond (Fig. 1). The circle had a diameter of 5.11°; similar to the stimuli used by Jacobsen and Höfel (2003). However, in our experiment, the background shapes were always present, and did not appear at the same time as symmetrical/random patterns elements. This was designed to give more insight into the influence of regularity on VEPs, which may otherwise be dominated by the onset of the white background.

2.1.5. Procedure
Participants sat in a darkened and electrically shielded room in front of the stimulus monitor. After the electrodes were attached, it was explained that they would be required to fixate on a central cross during the baseline period and when the patterns were on the screen. Each trial started with a fixation cross, which was on for 1.5 s, and was followed by a black and white pattern, which was on the screen for 3 s. The trial structure is shown in Fig. 1.

At the end of each trial, participants were prompted with a response screen to report whether they had seen a symmetrical or a random pattern. They had up to 3 s to enter an appropriate response. In all versions of Experiment 1 participants pressed one button for reflectional symmetry, and another for random patterns. However, there were two types of response screen in Experiment 1 (Table 1). In Experiment 1A, the response screen read: "reflection random" or: "random reflection". The left or right position of the words "random" and "reflection" on the response screen varied between trials, and the position indicated which key to press. For example, if the word "reflection" was on the left of the response screen, and the pattern was a reflection, then the correct key was the left key. The position of the words was counterbalanced across other factors, but was not predictable for the participants. Participants, therefore, did not know which hand to respond with until the response screen appeared. This prevented the development of lateralized motor preparation potentials during the stimulus presentation (Murray et al., 2004; Makin, Poliakoff, Ackerley, & El-Deredy, 2012). Because it is possible that the name of the categories could influence electrophysiological responses, we changed the wording of the response screen in Experiment 1B to "symmetry random" or "random symmetry".

The Experiment was divided into six blocks, and participants were given a break between each block, allowing them to rest their eyes and break fixation. Before the experiment, participants completed a practice block of 16 trials. The design of the practice block mirrored that of the subsequent experiment, with the exception that a beep sounded if an incorrect response was made. This training ensured that participants understood the task.

2.1.6. EEG analysis
Offline, the EEG trace was re-referenced to a scalp average, low-pass filtered at 25 Hz and then down sampled to 128 Hz to reduce file size. Data was then segmented into epochs from −1 to 1 s, and baseline corrected to a −200 to +50 ms interval around stimulus onset. This epoch was appropriate because previous analysis showed that all interesting ERP components happen within the first second of stimulus onset. For four participants, linear de-trending was used to remove to slow changes in amplitude across the two-second epoch. Independent Components Analysis (ICA) was used to identify and remove ocular and muscle artefacts (Jung et al., 2000). Data was broken into 64 independent components, and an average of 9.42 components was removed from each participant (min=4, max=16). After ICA, trials were removed if amplitude exceeded ±100 μV at any electrode or time point. The number of trials removed did not differ between the reflection and random conditions (10.34% vs. 9.95%, p=0.760)

Horizontal and vertical eye electrode channels were low-pass filtered at 25 Hz and epoched (−1 to 1 s), but not subjected to further treatment. Mean EOG activity did not differ between reflection and random conditions (VEOG, p=0.211; HEOG, p=0.185). This provides evidence that any remaining ocular artefacts (or side effects of artefact correction procedures) did not selectively distort one condition.

Time-frequency analysis was conducted on the same raw data as the ERP analysis. However, data was broken into −1 to 3 s epochs, because longer epochs are necessary to explore low frequency waves. Data was filtered at 1–25 Hz for this analysis[2]. After

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[2] Note that, unlike the ERP analysis, a 1 Hz hi-pass filter was used prior to time-frequency analysis. This had the advantage of removing slow waves from the EEG, and thereby allowing ICA to model other artefacts. As a results of this, fewer components and trials were removed. Despite the advantage of the 1 Hz hi-pass filter for data cleaning, there is a problem that hi-pass filters can erroneously bias the apparent latency of ERP components. In particular, a long, late component, like the sustained posterior negativity, can be pushed backwards in time, resulting in artificial changes in the amplitude of P1 or N1 (Luck, 2005, Chapter 5). This can be corrected with further manipulations, but it is best to avoid the problem altogether, particularly when making theoretical claims about VEP amplitude. We were also concerned that the 25 Hz low pass filter, or 128 Hz sampling rate could have temporally smeared the ERPs, resulting in erroneous claims about latency. In

ICA, trials were removed if amplitude exceeded $\pm 75\,\mu V$ at any electrode or time point (stronger criteria appropriate because the high pass filter removed high amplitude potentials). The number of trials removed was low and did not differ between the reflection and random conditions (4.06% vs. 4.90%, $p=0.133$). Frequency power from 4 to 20 Hz (in 0.5 Hz increments) was calculated relative to a 500 ms pre-stimulus baseline. Power values were extracted by multiplying the raw EEG data by an idealized *wavelet* of a certain frequency (Roach & Mathalon, 2008).

2.1.7. EMG analysis

EMG was processed according to norms in the literature and published guidelines (Achaibou et al., 2008; van Boxtel, 2010). The continuous ZM data was high pass filtered at 20 Hz, and divided into epochs from the -1 to 3 s from stimulus onset. At this stage, we removed trials where amplitude exceeded $\pm 75\,\mu V$ to avoid spurious outlier effects. The number of trials removed was small and did not differ significantly between conditions (1.30% vs. 1.20%, $p=0.692$). The EMG trace was then rectified (converted into an absolute score), and averaged over 500 ms time windows. Amplitude in each window was recomputed relative to a 1000 ms pre stimulus baseline period, and converted into a Z score (amplitude—baseline/SD across the whole epoch). Data from the CS muscle was processed in a similar way, except a $100\,\mu V$ exclusion criterion was employed. This was appropriate as the CS muscle had high baseline amplitude. Again, very few trials were removed (0.10% vs. 0.36%, $p=0.135$). It was necessary to measure activity in the CS to ensure ZM activations could not be attributed to non-specific facial responses (Winkielman et al., 2006).

2.2. Experiment 1 results

Twenty-four participants were presented with 80 reflection and 80 random patterns, each for three seconds. After this, a response screen appeared and they had to report which pattern they had just seen. Participants made the correct judgment on most trials (Mean correct$=96.58\%$, $SD=2.53\%$).

2.3. Event related potentials

Fig. 2A shows the grand-average ERP from the PO7 and PO8 electrodes (collapsed across all 24 participants in Experiments 1A and B). Separate lines show amplitude in the reflection and random conditions. Topographic maps in Fig. 2B show the *difference* between reflection and random conditions at key time windows. Red indicates higher amplitude in the reflection condition, while blue indicates higher amplitude in the random condition. As ERPs did not differ significantly between Experiment 1A and B, this factor was not included in statistical analysis.

2.3.1. Visual evoked potentials

The P1 component was not modulated by stimulus regularity (Fig. 2A). This was confirmed by analysis of amplitude at the PO7 and PO8 electrodes between 100 and 130 ms post stimulus onset. The difference between reflection and random trials was not significantly greater than zero ($M=0.20\,\mu V$; $t(23)=0.820$; $p=0.420$). This can be seen in the leftmost topographic plot in Fig. 2B, which depicts the difference between reflection and random conditions on the color axis. Unlike P1, N1 amplitude was sensitive to regularity. The difference between reflection and random conditions at 170–200 ms was greater than zero ($M=0.55\,\mu V$; $t(23)=2.294$; $p=0.031$), middle topographic plot, Fig. 2B).

2.3.2. Sustained posterior negativity

The next ERP modulation began around 250 ms post stimulus, and persisted until the end of the epoch (Fig. 2A). Amplitude was lower in the reflection condition, in tune with the sustained posterior negativity effect reported by Jacobsen and Höfel (2003). The effect can be seen in the rightmost topographic difference maps of

Fig. 2B. We explored this effect by analysing amplitude in the PO7/PO8 electrodes in the 300 to 1000 ms time bin. There difference between reflection and random was significantly greater than zero ($M=2.50\,\mu V$; $t(23)=7.003$; $p<0.001$). Source localization analysis of the difference wave in Fig. 2B, using low resolution electromagnetic tomography (LORETA, Pascual-Marqui, Michel, & Lehmann, 1994), revealed that this modulation was largely attributable to activity in the lateralized extrastriate visual cortex (Fig. 2C).

2.4. Event related desynchronization

In Fig. 3A, time-frequency spectrograms show power as a function of time and frequency in the left (PO3 and PO7) and right (PO4 and PO8) posterior electrode clusters. Topographic maps in Fig. 3B show the distribution of 10 to 14 Hz power at two instructive time windows. It can be seen that, in all conditions, 10–14 Hz ERD began around 500 ms post stimulus, and then gradually subsided towards the end of the epoch, and that ERD was more pronounced over the right hemisphere. To confirm these impressions, 10–14 Hz power was analyzed as a function of three within-subject factors [hemisphere (left posterior electrodes vs. right posterior electrodes), regularity (reflection vs. random), and time (0–2500 ms post stimulus, in 500 ms intervals)] and one between-subjects factor [Experiment version (1A, 1B)] with mixed-methods ANOVA. Each data point was averaged over a 40 ms window. The Greenhouse–Geisser correction factor was applied when the assumption of sphericity was violated.

There was a main effect of time, confirming that power in this frequency band significantly changed throughout the epoch ($F(2.42, 53.18)=10.861$; $p<0.001$). There was no overall difference between the reflection and random conditions ($F(1,22)<1$; N.S), but there was a main effect of Hemisphere ($F(1,22)=5.187$; $p=0.033$), because ERD was more pronounced on the right posterior cluster than the left. There was also a significant hemisphere $\times$ time interaction ($F(5,110)=2.570$; $p=0.031$), because the main effect of hemisphere was only significant at time points from 500 to 2000 ms post stimuli ($t(23)>2.072$; $p<0.050$). This interaction was the only effect that was significantly modulated by the between-subjects factor Experiment version ($F(1,110)=2.501$; $p=0.035$). This was because the hemisphere $\times$ time interaction reached significance in Experiment 1A ($F(5,55)=3.813$; $p=0.005$), but not Experiment 1B ($F(2.77,30.46)=1.034$; $p=0.387$). There were no other effects or interactions ($F(2.90,63.76)<2.316$; $p>0.085$).

2.5. Facial electromyography

The grand-average EMG responses from the smiling muscle (ZM) and frowning muscle (CS) were analysed with a mixed ANOVA, with two within subject factors [regularity (reflection, random) $\times$ time (250, 750, 1250, 1750, 2250, 2750 ms]. There were no differences between Experiment 1A and B, so we do not consider this factor further.

2.5.1. Smiling muscle (ZM)

ZM activation is shown as a function of time in the reflection and random conditions in Fig. 4A. There was no overall difference between reflection and random trials ($F(1,23)<1$; N.S.). There was a main effect of Time ($F(2.14,49.24)=3.660$; $p=0.030$), and a regularity $\times$ time interaction ($F(3.23,74.39)=3.102$; $p=0.028$). In the random condition smiling decreased over the 3 s epoch. In the reflection conditions, smiling decreased from 250 to 750 ms, but then increased again, to reach a peak at 1750 ms. This interaction is described by a significant linear contrast in the random condition ($F(1,23)=17.361$; $p<0.001$), but a significant cubic contrast in the reflection condition ($F(1,23)=19.522$; $p<0.001$).

(*footnote continued*)
particular, the N1 modulation could be artificial extension of the later sustained posterior negativity. We explored this by reanalysing the data from Experiment 2 with a 256 Hz sampling rate and 40 Hz low pass filter (similar to the parameters used by Höfel and Jacobsen (2007a)). This made no difference to the ERP waveforms.
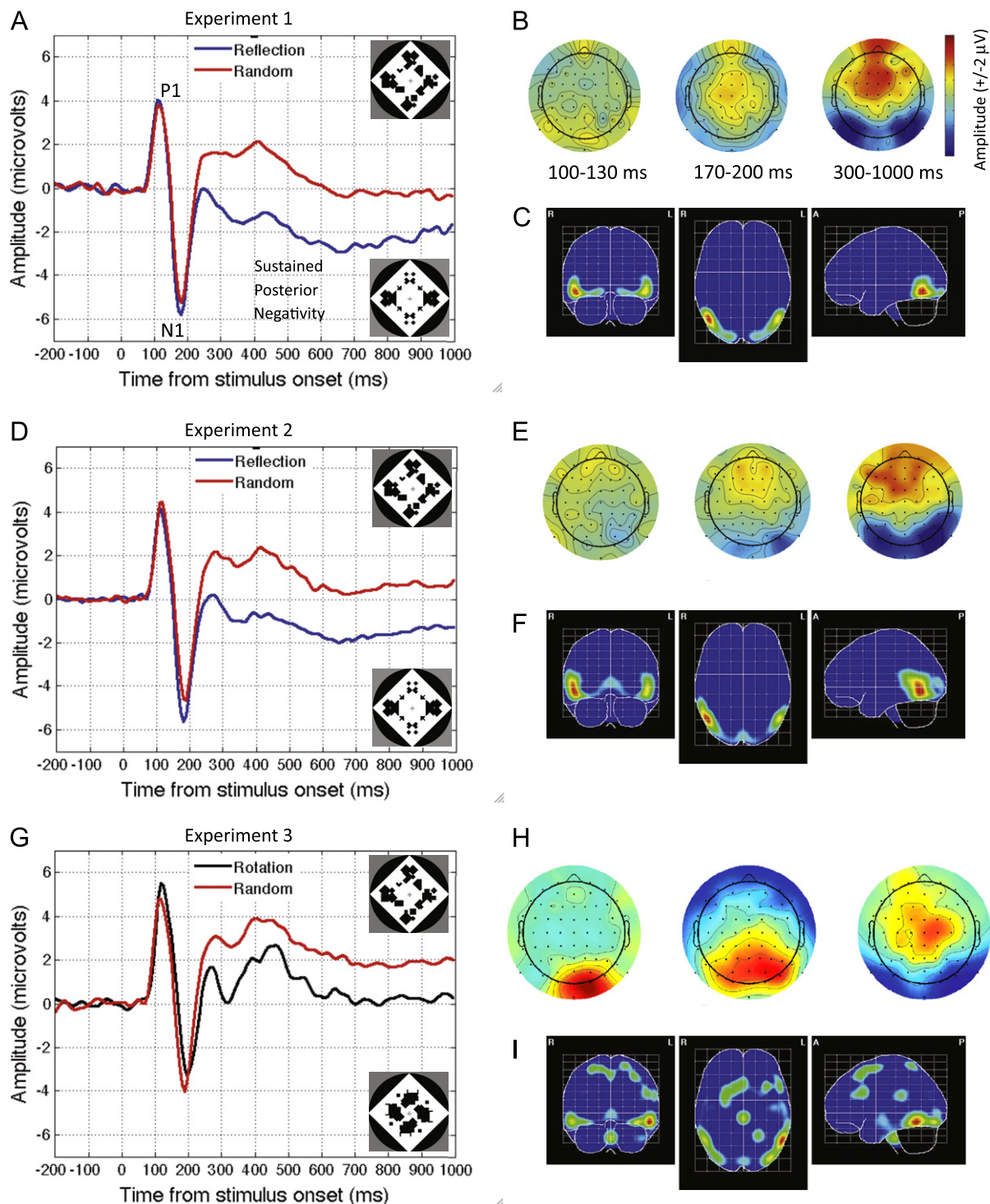
Fig. 2. ERPs. (A) ERPs from Experiment 1. Grand average ERPs from the PO7 and PO8 electrodes, in the reflection and random conditions. (B) Topographic difference maps from Experiment 1. Each map represents a head, and each black dot represents an electrode. The data shows amplitude in the reflection condition minus amplitude in the random condition across the time window labelled below. Red thus indicates greater amplitude in the reflection condition; blue indicates higher amplitude in the random condition. (C) LORETA source localization analysis. The data from the right grand average difference plot in B was used, and the estimated location of the generators is shown from three sections. Panels (D)–(F) show the corresponding data from Experiment 2. Panels (G)–(I) show the data from Experiment 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We also hypothesised that participants with more pronounced sustained posterior negativity might also show greater ZM responses (quantified as the change in differential ZM activity between the 750 and 1750 ms time bins). This prediction was confirmed, although the correlation was only marginally significant ($r = 0.348$; $p = 0.048$, one tailed).

2.5.2. Frowning muscle (CS)

Data from the CS muscle was analyzed in the same way as ZM. There was a main effect of time, because CS activation increased throughout the epoch ($F(1.94, 44.67) = 5.213$; $p = 0.01$, linear contrast ($F(1,23) = 6.187$; $p = 0.021$). However, unlike ZM, there were no other effects or interactions ($F(2.82, 64.84) < 1.997$; $p > 0.126$).
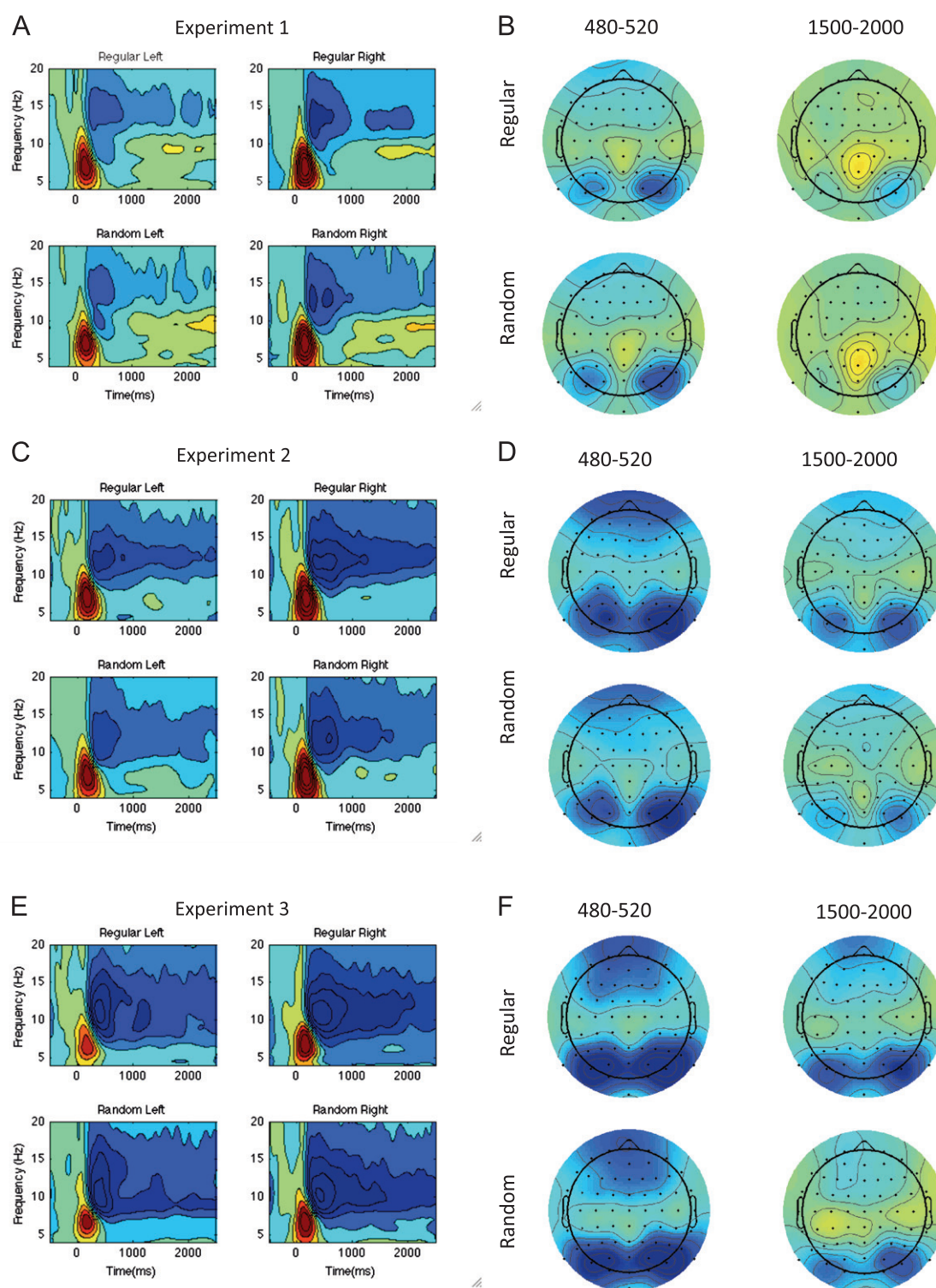
Fig. 3. Time-frequency analysis. (A) Time-frequency spectrograms from Experiment 1. Plots show frequency power as a function of time in the left (PO3 and PO7) and right (PO4 and PO8) posterior electrodes, in the reflection and random conditions. (B) Topographic maps show the scalp distribution of 10–14 Hz activity in the reflection and random trials in two time bins (480–500 ms post stimulus, and 1500–2000 ms post stimulus). Blue on the color axis means a reduction in oscillations at a particular frequency, i.e., event related desynchronization (ERD). Panels (C) and (D) show the corresponding data from Experiment 2. Panels (E) and (F) show data from Experiment 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.6. Experiment 1 discussion

Experiment 1 provided some evidence that reflectional symmetry patterns are spontaneously evaluated. The ZM muscle, responsible for smiling, was more active when participants viewed reflection than

random patterns. More specifically, smiling decreased during the first 750 ms of the epoch, but the selectively rebounded in the reflection condition. This affective response was observed despite the fact that participants were not asked to evaluate the patterns, challenging conclusions based on EEG data alone (e.g., Höfel & Jacobsen, 2007a).
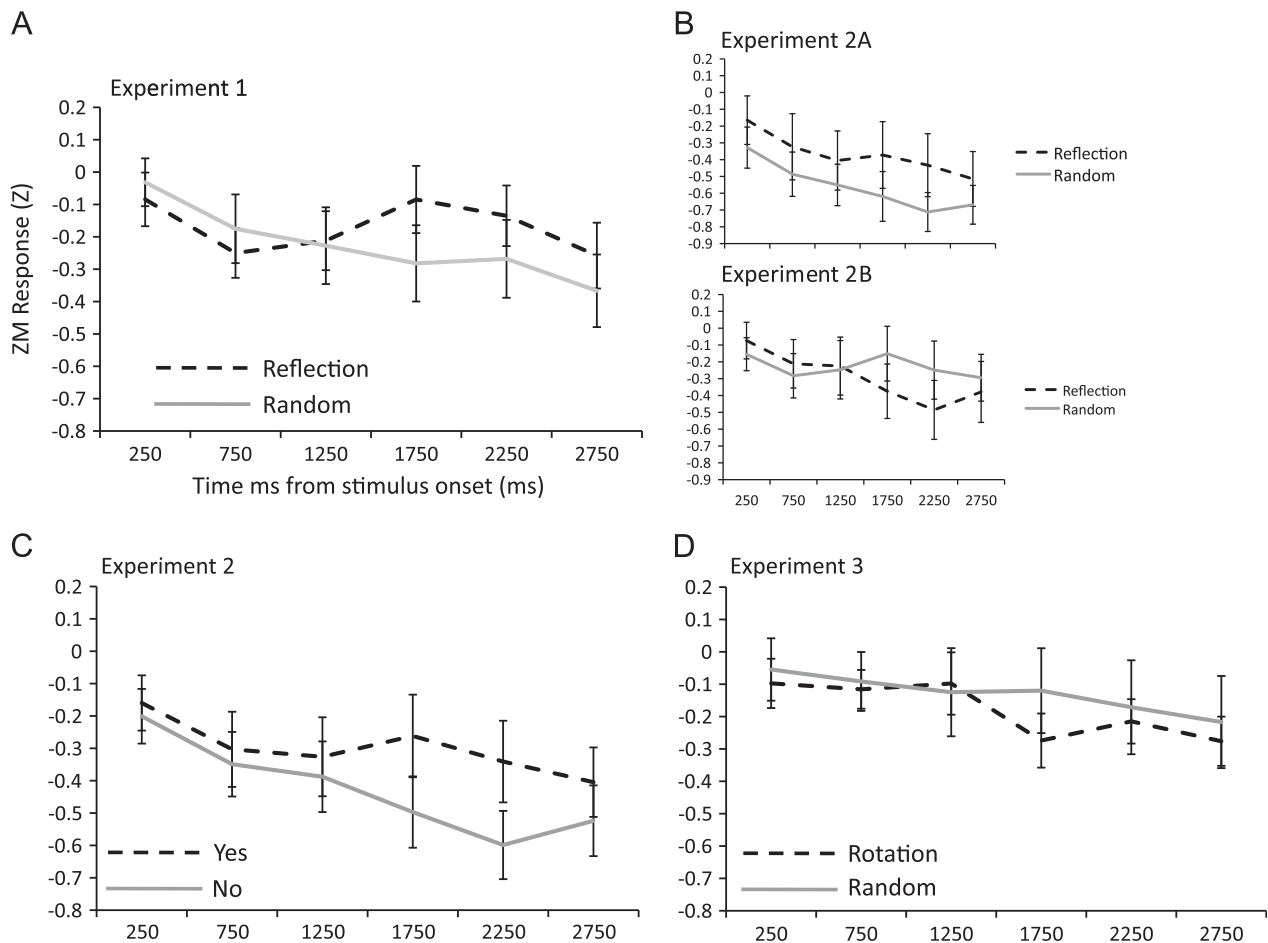
Fig. 4. (A) ZM activation in Experiment 1. Standardized ZM activity is shown in the reflection and random conditions as a function of time from stimulus onset. Data is collapsed across Experiments 1A and 1B. (B) ZM activation in Experiment 2A and 2B, shown in separate graphs. (C) ZM activation in the trials requiring YES and NO responses in Experiment 2. (D) ZM activation in Experiment 3. Each data point corresponds to activity averaged over a 500 ms window around the stated point. Error bars = ± 1S.E.M.

The ERP data from Experiment 1 revealed several instructive similarities and differences from previous work. First, we found that N1 amplitude was greater for reflection patterns. This suggests visual symmetry detection begins at an earlier stage in visual processing than previously thought (Treder, 2010). This could be because the background did not appear at the same time as the pattern elements in our Experiment 1, while this could have masked N1 modulations in previous studies. While our N1 modulation was novel, we did replicate the sustained posterior negativity reported by Jacobsen and Höfel (2003), and source localization using LORETA identified generators in the extrastriate visual cortex, consistent with previous neuroimaging work (Sasaki et al., 2005). This suggests our patterns were processed in the same way as stimuli used in previous experiments.

It was interesting to find a positive correlation between the amplitude of the sustained posterior negativity and ZM response in Experiment 1. Perhaps participants whose visual system is more sensitive to symmetry have a greater affective response to visual symmetry. This observation is consistent with the behavioral data reported in our earlier work (Makin et al., 2012a; Makin, Pecchinenda, & Bertamini, 2012b).

We also found that 10–14 Hz ERD was evident from about 500 ms post stimuli to the end of the epoch, and was more pronounced in the right posterior electrodes. This observation is consistent with the finding that symmetry detection involves visuospatial attention (Olivers & van der Helm, 1998), which is predominantly a right hemisphere function (Mesulam, 2002).

The wording of the response screen had no effect on the ERPs or facial muscle activations reported above—there were no significant differences between Experiment 1A and B, indicating that these effects were not dependent upon particular labels being applied to the regular pattern. Nevertheless, the issue of how the patterns were coded required further consideration. This was the subject of Experiment 2.

3. Experiment 2

Experiments 2 tested whether the results of Experiment 1 could be attributed to the task being recoded as a target present/target absent task. In 2AFC paradigms, people often perceive the more salient option as a *target* and the other as *absence of a target* (or 'figure' and 'ground' in the nomenclature of Rothermund & Wentura, 2004). In Experiments 2A and B, we overtly manipulated the status of the reflection and random patterns. All participants in Experiment 2 responded by pressing YES or NO buttons. In Experiment 2A participants pressed YES if they saw a reflection pattern, and pressed NO if they saw a random pattern. For these participants, reflection was the target category. In Experiment 2B, participants had the opposite protocol (YES for random, and NO for reflection, Table 1), so, for these participants, the random patterns were now the target category. We were interested in whether any of the effects found in Experiment

1 would be altered, or perhaps reversed, by this target manipulation in Experiment 2.

3.1. Experiment 2 method

Twenty-four participants (age 18 to 41, 8 male, 0 left-handed) took part; with 12 in Experiments 2A and B (none of these people had participated in Experiment 1). Stimuli were generated in the same way as Experiment 1. The position of the YES and NO buttons at the end of each trial was unpredictable, but counterbalanced with other factors. A linear de-trend procedure was used to remove high amplitude drift from one participant. Independent components were removed from the ERP epochs ($M=10.17$, range$=2$ to 19) and the time-frequency epochs ($M=5.91$, range$=1$–12). Few trials were excluded, with no differences between reflection and random conditions (ERP epochs 7.34% vs. 7.19%, $p=0.820$; time-frequency epochs: 4.17% vs. 4.22%, $p=0.920$; ZM epochs; 1.93% vs. 2.76%, $p=0.162$; CS epochs 5.83% vs. 5.26% $p=0.572$). EOG activity did not differ between conditions (VEOG, $p=0.771$, HEOG, $p=0.170$).

3.2. Experiment 2 results

In Experiment 2, participants were encouraged to treat one type of pattern as a target, and the other as the absence of a target. For 12 participants in Experiment 2A, the response screen encouraged them to perceive the reflection pattern as the target. For 12 participants in Experiment 2B, the random pattern was the target (Table 1). Participants were able to distinguish between reflection and random patterns easily, despite the slightly more complex response protocol (Mean correct$=94.90$%, $SD=5.81$%).

3.3. Event related potentials

ERP data was processed in the same way as Experiment 1. ERPs did not differ between Experiment 2A and B, so this factor is not included in analysis. Results are shown in Fig. 2D–F. It can be seen that the ERP waveform was similar to Experiment 1. The P1 modulation was not significant ($M=0.30\,\mu V$; $t(23)=1.504$; $p=0.140$), N1 was larger for the reflection patterns ($M=0.92\,\mu V$; $t(23)=3.995$; $p=0.001$), and the sustained posterior negativity was replicated ($M=2.32\,\mu V$; $t(23)=6.881$; $p<0.001$). LORETA revealed that the lateralized extrastriate visual areas generated this difference wave (Fig. 2F), again replicating the results of Experiment 1.

3.4. Event related desynchronization

Results from the time-frequency analysis are shown in Fig. 3C and D. Data was subjected to the same analysis as Experiment 1. There was a main effect of time ($F(2.32,50.98)=19.676$; $p<0.001$), confirming that power changed throughout the epoch. Unlike Experiment 1, there was no main effect of hemisphere ($F(1,22)=1.690$; $p=0.207$). Also unlike Experiment 1, there was a main effect of regularity, because ERD was more pronounced in the reflection condition ($F(1,22)=9.346$; $p=0.006$). This effect interacted with between-subjects factor Experiment type ($F(1,22)=6.530$; $p=0.018$), because the effect of regularity was far stronger in Experiment 2A, where reflection was the target pattern ($F(1,11)=15.856$; $p=0.002$), than in Experiment 2B, where random was the target pattern ($F(1,11)<1$; N.S). There were no other effects or interactions ($F(1.99,43.70)<3.073$; $p>0.056$).

It is of interest that ERD 10–14 Hz band was more pronounced in Experiment 2 than Experiment 1, although in further analysis comparing the experiments this between-subjects effect did not reach significance ($F(1, 46)=3.637$; $p=0.063$).

3.5. Facial electromyography

ZM activation was analysed with a mixed ANOVA with two within-subject factors [regularity (reflection, random) $\times$ time (250, 750, 1250, 1750, 2250, 2750)] and one between-subjects factor [experiment version (2A, 2B)].

There was no overall difference in ZM activity between reflection and random trials ($F(1,22)=<1$; N.S) but there was a main effect of time, ($F(3.09,68.01)=8.10$; $p<0.001$). There was no regularity $\times$ time interaction ($F(2.57,56.61)<1$; NS). However, there was also a borderline significant three-way interaction between regularity, time and the between-subjects factor Experiment version ($F(2.57,56.61)=2.742$; $p=0.060$). This interaction can be seen by comparing the data from Experiments 2A and 2B (Fig. 4B). The simplest way to describe this effect is by noting that participants smiled more for the target pattern which required them to press the YES button. Data is plotted separately for conditions requiring YES and NO responses in Fig. 4C. The NO line in this plot can be described by a significant linear contrast only ($F(1,23)=15.733$; $p=0.001$). Conversely, the YES line was characterized by significant linear ($F(1,23)=4.761$; $p=0.04$) and cubic contrasts ($F(1,23)=10.826$; $p=0.003$).

There was no correlation between the amplitude of the sustained posterior negativity and the ZM response ($r=0.084$, $p=0.349$, one tailed). This is unsurprising because the target/no target manipulation reversed the ZM response, but not ERPs in Experiment 2.

The CS muscle was analyzed in the same way as Experiment 1, and the results were similar to Experiment 1. There were no differences between Experiment 2A and B. The only significant effect was a main effect of Time ($F(2.057,47.302)=6.254$, $p=0.004$), produced by an increase in CS activation towards the end of the trial (linear contrast, $F(1,23)=8.445$, $p=0.008$).

3.6. Experiment 2 discussion

While Experiment 1 provided some evidence that reflection patterns are spontaneously evaluated, Experiment 2 provided a more nuanced account. In Experiment 1, The ZM muscle was more active on viewing reflection than random patterns by 1750 ms post stimulus. In Experiment 2, we contrasted conditions where reflection and random patterns were designated the target stimulus. The ZM response now depended on the target type rather than simply on the presence of reflectional symmetry. The ZM data from Experiment 2 suggest that this response is driven by detection of a search item, rather than the presence of reflectional symmetry per se. This can be contrasted with the sustained posterior negativity, which is an electrophysiological response to symmetry, irrespective of task parameters. Because of this, the ERP and ZM response were no longer correlated in Experiment 2.

The ERPs in Experiment 2 were very similar to Experiment 1, showing that this brain activity is driven by stimulus characteristics, rather than response criteria. Again there was no P1 modulation, but there were significant differences between reflection and random waveforms at the N1 latency, and the sustained posterior component was replicated. A new effect in Experiment 2 was that 10–14 Hz ERD was sensitive to regularity, and particularly when reflection patterns were the target stimuli in Experiment 2A. This effect was predicted, and it could be another manifestation of the extrastriate visual activations reported by Sasaki et al. (2005). It seems likely that ERD was especially sensitive to regularity in Experiment 2A because this

was the only condition where symmetry overtly designated as a target, requiring a YES response.

4. Experiment 3

Previous neuroimaging work has mainly focused on reflectional symmetry, which is only one type of visual regularity. We therefore investigated the electrophysiological responses produced by rotational symmetry in Experiment 3. Previous psychophysical data suggests that detection of rotational symmetry is slower than reflectional symmetry (Palmer & Hemenway, 1978; Royer, 1981), so we anticipated differences in the ERP components, and possibly in affective responses[3].

4.1. Experiment 3 method

Most aspects of Experiment 3 were identical to that of Experiment 1, with the exception that participants were presented with either rotational symmetry or random patterns. In order to facilitate comparison with Experiment 1, we used the words SYMMETRY and RANDOM on the response screen. Participants pressed the A and L keys depending on the layout of the response screen and the nature of the target. Twelve participants (age 21 to 51; 5 male; 0 left-handed) were involved (none of these people had participated in Experiment 1 or 2).

As in Experiment 1, few independent components were removed from the ERP epochs ($M=9.08$, range$=6$–12) and from the time-frequency epochs ($M=6.91$, range$=4$–10). No linear detrending was necessary. Few trials were excluded, with no differences between rotation and random conditions (ERP epochs 1.45% to 1.04%, $p=0.166$; time-frequency epochs: 1.56% vs. 2.08%, $p=0.516$; ZM epochs; 1.15% vs. 1.56%, $p=0.586$; CS epochs 2.29% vs. 3.34% $p=0.233$). Activity in the EOG channels did not significantly differ between conditions (VEOG, $p=0.824$, HEOG, $p=0.051$).

4.2. Experiment 3 results

The participants found it easy to discriminate between rotation and random patterns (Mean percent correct$=94.95\%$, $SD=2.9\%$). However, the ERPs produced by rotational symmetry were different from those produced by reflectional symmetry in Experiments 1 and 2. Unlike Experiments 1 and 2, there was a difference between the regular and random patterns at the P1 latency (Fig. 2G), which was strongest at the O2 electrode ($M=2.03$ μV; $t(11)=3.188$; $p=0.009$, Fig. 2H). Also unlike Experiments 1 and 2, N1 was greater in the random than regular condition ($M=1.27$ μV; $t(11)=3.845$; $p=0.003$). The sustained posterior negativity was less pronounced in Experiment 3, although still significant, ($M=1.68$ μV; $t(11)=6.501$; $p<0.001$).

[3] We wanted to ensure that previous psychophysical results applied to our participants and stimuli. Before the main experiments, participants first completed a speeded discrimination task. Participants were presented with 30 regular and 30 random patterns (like those shown in Fig. 1), and had to classify them as quickly as possible. Before Experiment 1 and 2, participants discriminated reflection from random patterns, before Experiment 3, they discriminated rotation from random patterns. In the reflection/random speeded discrimination task, participants were quicker to respond to reflection ($M=717$ ms) than random patterns ($M=779$ ms). This difference was significant ($t(47)=4.319$; $p<0.001$). In the rotation/random speed discrimination task; there was no difference in reaction time between the rotation ($M=866$ ms) and random ($M=951$ ms) conditions ($t(11)=1.249$; $p=0.238$). The average response times for rotation/random discrimination was 908 ms, which is longer than the reflection/random discrimination speed associated (748 ms). This difference was significant ($t(18.80)=2.555$; $p=0.020$, equal variances not assumed), therefore the detection speed differences reported in the literature were replicated with our participants.

LORETA identified generators around the extrastriate visual cortex (Fig. 2I), although this was far less clear-cut than in Experiments 1 and 2.

Time-frequency data is shown in Fig. 3E and F. The same statistical analysis was applied to this data. There was again a significant main effect of time ($F(2.23,24.50)=14.226$; $p<0.001$). Although there were no main effects of hemisphere or regularity ($F(1,11)<3.161$; $p>0.102$), there was a hemisphere $\times$ time interaction ($F(5,55)=3.877$; $p=0.004$). This was because ERD was more pronounced on the right at 1000 and 2000 ms post stimuli ($t(11)>2.309$; $p<0.042$). There were no other effects or interactions ($F(5,55)<1$; N.S). Subsequent analysis found that ERD was larger in Experiment 3 than Experiment 1 ($F(1,34)=5.159$; $p=0.03$), but there was no difference between Experiment 3 and Experiment 2 ($F(1,34)<1$; N.S).

EMG data was processed in the same way as in Experiment 1. ZM activation decreased over the course of the trial, producing a main effect of time ($F(2.95,32.41)=3.002$; $p=0.046$; linear contrast $F(1,11)=8.142$; $p=0.016$; Fig. 4D). There were no other effects or interactions ($F(2.50,27.46)<1$; N.S). There were no main effects or interactions regarding the CS data ($F(5,55)<2.120$; $p>0.076$).

4.3. Experiment 3 discussion

Experiment 3 found that the electrophysiological responses to reflectional symmetry recorded in Experiments 1 and 2 and did not uniformly generalize to rotational symmetry. In Experiment 3, there was a novel P1 modulation. N1 modulation was in the opposite direction to that recorded in Experiments 1 and 2. These differences suggest that rotational symmetry discrimination begins earlier than reflectional symmetry discrimination, challenging reliable psychophysical evidence (Palmer & Hemenway, 1978; Royer, 1981). Experiment 3 also demonstrated that the sustained posterior negativity is generated by rotational symmetry as well as reflectional symmetry. We can conclude that generalized regularity sensitive networks, rather than specialized reflection detectors, generate this component. Nevertheless, this ERP was reduced for rotation, suggesting that reflection might be the preferred stimulus for these networks. Finally, there were no clear differences in 10–14 Hz ERD between rotation and random patterns, while analysis of facial muscle activity found no affective responses.

5. General discussion

In Experiment 1, participants had to classify abstract patterns in one of two categories based on whether reflectional symmetry was present or not. We tested whether reflectional symmetry would elicit an affective response, detectable in the facial muscle responsible for smiling. In addition, we predicted that VEP amplitude and upper alpha ERD would be affected by the reflection/random manipulation. In Experiment 2, we asked whether participants recoding the patterns as target and non-target stimuli could explain the observed effects. Finally, in Experiment 3, we tested whether these findings of Experiment 1 and 2 generalized to rotational symmetry. In this section we interpret each effect in chronological order, beginning with effects that occurred earlier after stimulus onset.

5.1. VEP modulation

In Experiments 1 and 2, The N1 was slightly larger for reflection patterns than random patterns. Other work has not found symmetry-related modulations at this latency (Jacobsen & Höfel, 2003, Höfel & Jacobsen, 2007a,b, Norcia, Candy, Pettet,

Vildavski, & Tyler, 2002, Oka, Victor, Conte, & Yanagida, 2007), so what could explain this difference? The N1 is sensitive to visual properties such as size and luminance, so it is important to consider all extraneous factors that could have co-varied with the regular/random manipulation in our experiments. On average, all quadrants had the same luminance, number of edges, and number of different orientations. The only remaining possibility is that random patterns were more variable, as every quadrant had an independently generated pattern. Nevertheless, this was true of previous studies, which did not find a N1 effect. It is possible that N1 effects were masked in previous studies by the onset of a white background at the same time as the pattern elements.

Experiment 3 provided the most interesting VEP modulations. Here both P1 and N1 were sensitive to pattern regularity. This is surprising, because most behavioral work has demonstrated that reflection/random discrimination is quicker than rotation/random discrimination (including the speeded discrimination task administered to our participants, see footnote 3). One might expect that early VEP modulations would be more pronounced for the more rapidly detected reflection patterns, but we found the opposite result. It is perhaps instructive that symmetry does not pop out in visual search tasks (Olivers & van der Helm, 1998), implying that spatial attention is a factor in symmetry perception. Perhaps spatial attention was more important for rotation discrimination than reflection discrimination, and this had a top-down influence on the early stages of visual processing? It could be that rotation detection requires effortful matching between orientation information and pattern elements—operations involving reciprocal connections with lower visual areas (van der Zwan et al., 1998), while reflection is more easily detected by regularity sensitive networks in the extrastriate cortex, so this kind of matching is unnecessary. However, we recognize that this distinction may only apply when rotation angle is relatively large: When glass patterns are used, the regularity is easily detected as long as the rotation angle is small (Wagemans et al., 1993).

5.2. Sustained posterior negativity

In all Experiments, amplitude was lower in the regular condition than the random condition from ∼250 ms to the end of the epoch. This resembles ERPs reported in other work. For example, Jacobsen and Höfel (2003) and Höfel and Jacobsen, (2007a,b) reported a sustained posterior negativity for symmetrical patterns, which was topographically similar to that reported here.

Three fMRI studies have identified activations in the visual cortex using reflection vs. random contrasts. Tyler et al. (2005) found reflectional symmetry activated the Lateral Occipital Cortex (LOC). Following this, Sasaki et al. (2005) found a similar effect in the LOC, but with additional activations in other extrastriate regions V3a, V4 and V7. Finally, Chen et al. (2007) found that reflectional symmetry (either in frontal images of faces or abstract patterns) activated intraoccipital sulcus and medial occipital gyrus (areas overlapping with the LOC), while the right occipital face area was uniquely sensitive to symmetry in faces. None of these neuroimaging studies have found symmetry dependent activations in V1 or V2. Source localization of the sustained posterior negativity estimated that this component was generated by brain areas similar to those identified by fMRI, although spatial resolution was not sufficient for detailed anatomical analysis.

The sustained posterior negativity was less pronounced when rotational symmetry was presented in Experiment 3, and the anatomical location of the generators was less precisely defined. This pattern of results implies that reflection might be a preferred stimulus for regularity-sensitive networks in the visual system. In fact, the salience of visual regularity can be manipulated in many

ways; for example, rotational symmetry becomes more apparent when the angle of rotation is reduced (Wagemans et al., 1993), and the salience of reflection and rotation can be altered by gestalt grouping principles (Bertamini, Friedenberg, & Kubovy, et al., 1997; Bertamini et al., 2002; Bertamini, 2010). It would be interesting to see whether these visual manipulations systematically map onto changes in amplitude of the sustained posterior negativity.

5.3. Event related desynchronization

We analyzed changes in the upper alpha range (10–14 Hz) following the onset of regular and random patterns. After the onset of the patterns, there was clear event related desynchronization 10–14 Hz over posterior electrodes. This ERD began at around 500 ms post stimuli, and then gradually reduced towards the end of the epoch. ERD was right lateralized in some conditions, and never left lateralized. This is possibly because symmetry discrimination involves visuospatial attention, which is predominantly a right-hemisphere function (Mesulam, 2002). However, neuroimaging studies on symmetry have not consistently reported right lateralized activations (e.g., Sasaki et al., 2005), and right lateralization of ERD was not universal in our study, so this claim demands caution. More interestingly, in Experiment 2, ERD was more pronounced for reflection patterns than random patterns, but only when reflection was overtly designated the target stimuli. This implies that ERD is sensitive to the presence of visual symmetry but also its task relevance. Considering all ERD analysis, the take-home message is that visual symmetry perception involves upper alpha ERD, but this measure is further modulated by other task parameters, a systematic account of which could be provided by future work.

5.4. ZM

In Experiment 1, ZM activity was greater for the reflection than the random patterns in the second half of the trial. Winkielman et al. (2006) found a similar response to prototypical dot patterns. It is interesting that symmetry and prototypicality are well known determinants of subjective preference (Ramachandran & Hirstein, 1999), and therefore it is perhaps unsurprising that they should produce a similar pattern of ZM muscle activation.

Experiment 2 complicated this simple story. In Experiment 2, participants responded by choosing a YES or a NO option (Fig. 1). Half the participants were asked whether they had seen a reflection pattern (YES or NO) and half were asked whether they had seen a random pattern (YES or NO). We found that participants smiled more on trials that required a YES response, irrespective of whether the target was a reflection or a random pattern. It is likely that people respond positively to target stimuli that they are encouraged to look for.

This relates to the figure—ground distinction discussed by Rothermund and Wentura (2004). When presented with a two-alternative forced choice task, the more salient category becomes the figure. Salience may depend on many things, but in Experiment 1, the reflection patterns probably became the figure category, and the random became the ground. Taken together, the ZM data show that people spontaneously prefer the figure, and that they typically chose these reflection patterns as the figure, even without explicit instruction.

This finding has important methodological implications for EMG researchers. It is possible that asking participants to make any discrimination could result in a ZM response to the target category. To give an arbitrary example from a paper cited above, Achaibou et al. (2008) asked participants to report whether a face they had seen was happy or angry. This kind of categorization

task could theoretically be reduced to a present/absent judgment for the more salient category, with an emotional response being elicited by the *stimulus present* signal. This is not intended as a specific criticism, and it is entirely possible that genuine emotional responses to the stimuli were present in Achaibou et al. (2008) study. However, EMG researchers should be mindful of this methodological issue in future.

6. Conclusions

The current EEG/EMG study revisited two findings from previous work. First, it has been concluded that aesthetic evaluation of visual symmetry is a deliberate, intentional process rather than an automatic, spontaneous process. Even though our tasks did not involve explicit evaluation, we found that ZM activity differed after viewing reflectional symmetry compared to random patterns, suggesting a positive affective response to reflection. However, we also found that the designation of what is the target can reverse this effect. A more nuanced model of automatic evaluation is required. We conclude that the choice of reflectional symmetry as a target, and affective responses to the presence of a target, happen spontaneously, without instruction. This affective response can be detected with ZM muscle recordings, if not with ERPs.

Second, previous results have suggested that early sensory processing is unaffected by symmetry, but conversely, we found that VEP amplitude was modulated by regularity. Most interestingly, the P1 component was larger when rotational symmetry was presented. This could be because the crucial pattern elements appeared independently of the uniform background in our experiments. This implies that lower areas of the ascending visual hierarchy, possibly including V1, play a different role during rotational symmetry discrimination, perhaps because this rotation detection is more difficult, and demands more top-down attentional control in order to compare the relative position of the pattern elements. This intriguing result was not anticipated from existing reaction time or fMRI data, and warrants further investigation.

Acknowledgments

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