

The human visual system preserves the hierarchy of 2-dimensional pattern regularity

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1 A century of vision research has demonstrated that symmetry contributes to numerous domains of visual perception (1–4). In a 2-D image, the
2 four fundamental symmetries, reflection, rotation, translation and glide reflection, can be combined in 17 distinct ways. These 17 “wallpaper”
3 groups (5–7) obey a hierarchy, determined by mathematical group theory, in which simpler groups are subgroups of more complex ones(8).
4 Here we probe representations of symmetries in wallpaper groups using two methods: (1) Steady-State Visual Evoked Potentials (SSVEPs)
5 recorded using EEG and (2) symmetry detection thresholds measured psychophysically. We find that hierarchical relationships between the
6 wallpaper groups are almost perfectly preserved in both behavior and response amplitudes in visual cortex. This remarkable consistency
7 between the structure of symmetry representations and mathematical group theory, is likely generated over visual development, through
8 implicit learning of regularities in the environment.

Keyword 1 | Keyword 2 | Keyword 3 | ...

1 **S**ymmetries are present at many scales in images of natu-
2 ral scenes, due to a complex interplay of physical forces
3 that govern pattern formation in nature. The importance of
4 symmetry for visual perception has been known at least since
5 the gestalt movement of the early 20th century. Since then,
6 symmetry has been shown to contribute to the perception of
7 shapes (1, 3), scenes (4) and surface properties (2), as well as
8 the social process of mate selection (9). Most of this work has
9 focused on mirror symmetry or *reflection*, with much less attention
10 being paid to the other fundamental symmetries: *rotation*,
11 *translation* and *glide reflection*. In the two spatial dimensions
12 relevant for images, these four fundamental symmetries can be
13 combined in 17 distinct ways, the “wallpaper” groups (5–7).
14 Previous work has focused on four of the wallpaper groups,
15 and used functional MRI to show that rotation symmetries
16 within wallpapers are represented parametrically in several
17 areas in occipital cortex, beginning with visual area V3 (10).
18 This effect is also robust in electroencephalography (EEG),
19 whether measured using Steady-State Visual Evoked Poten-
20 tials (SSVEPs)(10) or event-related paradigms (11). Here we
21 extend on this work by collecting SSVEPs and psychophysical
22 data from human participants viewing the complete set of
23 wallpaper groups. We measure responses in visual cortex to
24 16 out of the 17 wallpaper groups, with the 17th serving as a
25 control stimulus, with the goal of providing a more complete
26 picture of how wallpaper groups are represented in the human
27 visual system.

28 A wallpaper group is a topologically discrete group of isome-
29 tries of the Euclidean plane, i.e. transformations that preserve
30 distance (7). Wallpaper groups differ in the number and
31 kind of these transformations. In mathematical group theory,
32 when the elements of one group is completely contained in
33 another, the inner group is called a subgroup of the outer
34 group (7). Subgroup relationships between wallpaper groups
35 can be distinguished by their indices. The index of a subgroup
36 relationship is the number of cosets, i.e. the number of times
37 the subgroup is found in the outer group (7). As an example,

let us consider groups P6 and P2. If we ignore the translations
in two directions that both groups share, group P6 consists of
the set of rotations $0^\circ, 60^\circ, 120^\circ, 180^\circ, 240^\circ, 300^\circ$, in which
P2 $0^\circ, 180^\circ$ is contained. P2 is thus a subgroup of P6, and
the full P6 set can be generated by every combination of P2
and rotations $0^\circ, 120^\circ, 240^\circ$. Because P2 is repeated three
times in P6, P2 is a subgroup of P6 with index 3 (7). The 17
wallpaper groups thus obey a hierarchy of complexity where
simpler groups are sub-groups of more complex ones (8). The
full set of subgroup relationships is listed in Section 1.4.2 of
the Supplementary Material.

The two datasets presented here puts on in the position
of being able to assess the extent to which both behavior
and brain responses follow that hierarchy. The results show
that activity in human visual cortex is remarkably consist-
ent with the hierarchical relationships between the wallpaper
groups, with SSVEP amplitudes and psychophysical thresh-
olds preserving these relationships at a level that is far beyond
chance. Visual cortex thus appears to encode all of the fun-
damental symmetries using a representational structure that
closely approximates the subgroup relationships from group
theory. Given that most participants had no knowledge of
group theory, the ordered structure of visual responses to
wallpaper groups is likely learned implicitly from regularities
in the visual environment.

Results

The stimuli used in our two experiments were multiple ex-
emplar images belonging to each of the wallpaper groups,
generated from random-noise textures, as described in detail
elsewhere (10). Exemplar images from group P1 was used as
control stimuli, and each exemplar from the other 16 groups
had a power-spectrum matched P1 exemplar. The matched
P1 exemplars were generated by phase-scrambling the exem-
plar images. Because all wallpapers are periodic due to their
lattice tiling structure, the phase-scrambled images all belong

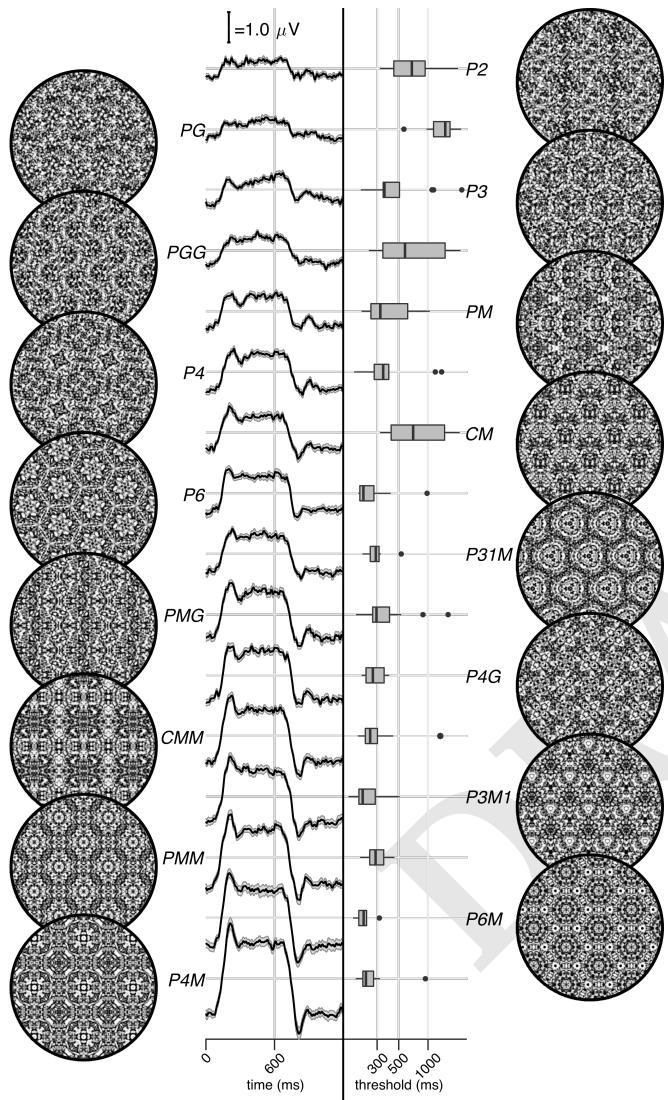
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Fig. 1. Examples of each of the 16 wallpaper groups are shown in the left- and right-most column of the figures, next to to the corresponding SSVEP (center-left) and psychological (center-right) data from each group. The SSVEP data are odd-harmonic-filtered cycle-average waveforms. In each cycle, a P1 exemplar was shown for the first 600 ms, followed by the original exemplar for the last 600 ms. Errorbars are standard error of the mean. Psychological data are presented as boxplots reflecting the distribution of display duration thresholds. The 16 groups are ordered by the strength of the SSVEP response, to highlight the range of response amplitudes.

to group P1 regardless of group membership of the original exemplar. P1 contains no symmetries other than translation, while all other groups contain translation in combination with one or more of the other three fundamental symmetries (reflection, rotation, glide reflection) (7). In our SSVEP experiment, this stimulus set allowed us to isolate brain activity specific to the symmetry structure in the exemplar images from activity associated with modulation of low-level features, by alternating exemplar images and control exemplars. In this design, responses to structural features beyond the shared power spectrum, including any symmetries other than translation, are isolated in the odd harmonics of the image update frequency (10, 12, 13). Thus, the combined magnitude of the odd harmonic response components can be used as a measure of the overall strength of the visual cortex response.

The psychophysical experiment took a distinct but related approach. In each trial an exemplar image was shown with its matched control, one image after the other, and the order varied pseudo-randomly such that in half the trials the original exemplar was shown first, and in the other half the control image was shown first. After each trial, participants were told to indicate whether the first or second image contained more structure, and the duration of both images was controlled by a staircase procedure so that a display duration threshold could be computed for each wallpaper group.

A summary of our brain imaging and psychophysical measurements is presented with examples of the wallpaper groups in Figure 1. For our primary SSVEP analysis, we only considered EEG data from a pre-determined region-of-interest (ROI) consisting of six electrodes over occipital cortex (see Supplementary Figure 1.1). SSVEP data from this ROI was filtered so that only the odd harmonics that capture the symmetry response contribute to the waveforms. While waveform amplitude is quite variable among the 16 groups, all groups have a sustained negative-going response that begins at about the same time for all groups, 180 ms after the transition from the P1 control exemplar to the original exemplar. To reduced the amplitude of the symmetry-specific response to a single number that could be used in further analyses and compared to the psychophysical data, we computed the root-mean-square (RMS) over the odd-harmonic-filtered waveforms. The data in Figure 1 are shown in descending order according to RMS. The psychophysical results, shown in box plots in Figure 1, were also quite variable between groups, and there seems to be a general pattern where wallpaper groups near the top of the figure, that have lower SSVEP amplitudes, also have longer psychophysical display duration thresholds.

We now wanted to quantify the degree to which our two measurements were consistent with the subgroup relationships. We hypothesized that more complex groups would (a) produce symmetric-specific SSVEPs with higher amplitudes and (b) shorter display duration thresholds. [PERHAPS WE NEED TO JUSTIFY THESE ASSUMPTIONS] We tested each of these hypotheses using the same approach. We first fitted a Bayesian model with wallpaper group as a factor and participant as a random effect. We fit the model separately for SSVEP RMS and psychophysical data, and then computed posterior distributions for the difference between supergroup and subgroup. These difference distributions could allowed us to compute the conditional probability that the supergroup would produce (a) larger RMS and (b) a shorter threshold

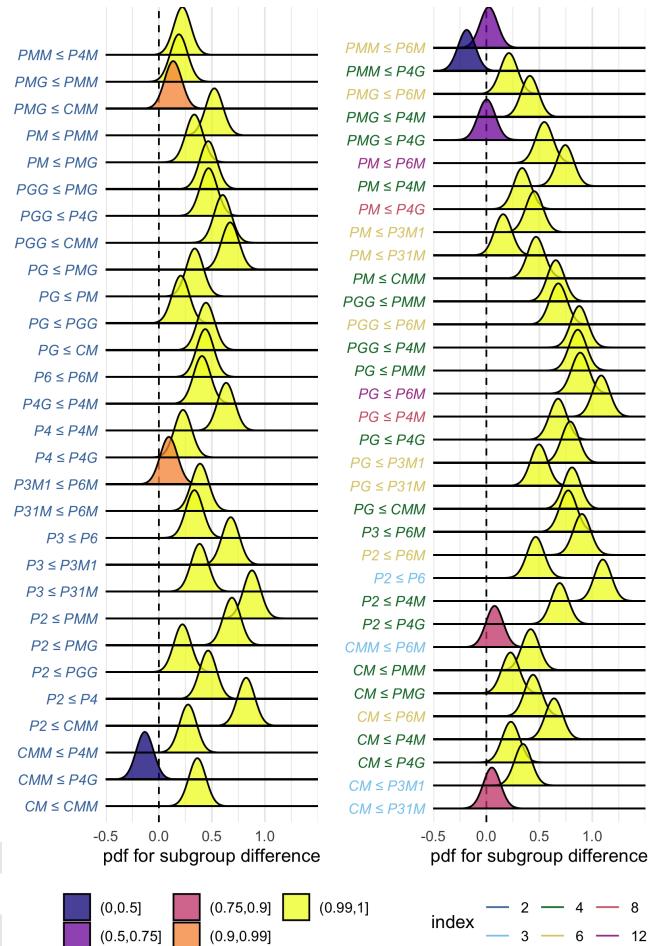
134 durations, when compared to the subgroup. The posterior
 135 distributions are shown in Figure 2 for the SSVEP data, and
 136 in Figure 3 for the psychophysical data, which distributions
 137 color-coded according to conditional probability. For both
 138 data sets our hypothesis is confirmed: For the overwhelming
 139 majority of the 64 subgroup relationships, supergroups are
 140 more likely to produce larger symmetry specific SSVEPs and
 141 shorter threshold durations, and in most cases the conditional
 142 probability of this happening is extremely high.

143 We also ran a control analysis using (1) odd-harmonic
 144 SSVEP data from a six-electrode ROI over parietal cortex (see
 145 Supplementary Figure 1.1) and (2) even-harmonic SSVEP data
 146 from the same occipital ROI that was used in our primary
 147 analysis. By comparing these two control analysis to our
 148 primary SSVEP analysis, we can address the specify of our
 149 effects in terms of location (occipital cortex vs parietal cortex)
 150 and harmonic (odd vs even). For both control analyses (plotted
 151 in Supplementary Figures 3.3 and 3.4), the correspondence
 152 between data and subgroup relationships was weaker than in
 153 the primary analysis. We can quantify the strength of the
 154 association between the data and the subgroup relationships,
 155 by asking what proportion of subgroup relationships that
 156 reach or exceed a range of probability thresholds. This is
 157 plotted in Figure 4, for our psychophysical data, our primary
 158 SSVEP analysis and our two control SSVEP analyses. It is
 159 that odd-harmonic SSVEP data from an occipital ROI and
 160 display duration thresholds both have a strong association
 161 with the subgroup relations, that for a clear majority of the
 162 subgroups survive even at the highest threshold we consider
 163 ($p(\Delta > 0 | \text{data}) > 0.99$), and that the association is far weaker
 164 for the two control analyses.

165 SSVEP data from four of the wallpaper groups (P2, P3,
 166 P4 and P6) was previously published as part of our earlier
 167 demonstration of parametric responses to rotation symmetry
 168 in wallpaper groups(10). We replicate that result using our
 169 Bayesian approach, and find the same parametric effect in
 170 the psychophysical data (Supplementary Figure 4.1 - NEEDS
 171 TO BE LABELED IN THE SM). We also conducted analyses
 172 looking for effects of index and normality in our two datasets,
 173 and found that ... Finally, we conducted a correlation analysis
 174 comparing SSVEP and behavioral data, and found a small
 175 ($R^2 = 0.44$) but above-zero correlation, as indicated by our
 176 confidence intervals. There are several factors that might
 177 explain the relatively weak correlation, most prominently the
 178 fact that the same individuals did not participate in each of
 179 the two experiments. Nevertheless, we find the relationship
 180 between the two datasets interesting, because it suggests that
 181 our psychophysical and SSVEP measurements are tapping
 182 into the same underlying mechanisms.

183 Discussion

184 Here we show that beyond merely responding to the elementary
 185 symmetry operations of reflection (14) and rotation (10),
 186 the visual system explicitly represents hierarchical structure
 187 of the 17 wallpaper groups, and thus the compositions of all
 188 four of the fundamental symmetry transformations (rotation,
 189 reflection, translation, glide reflection) which comprise regular
 190 textures. The RMS measure of SSVEP amplitude, preserves
 191 the complex hierarchy of subgroup relationships among the
 192 wallpaper groups (8). This remarkable consistency was specific
 193 to the odd harmonics of the stimulus frequency, that capture



194 **Fig. 2.** Posterior distributions for the difference in mean RMS SSVEP response.
 195 Colour coding of the text indicates the index of the subgroup, while the colour of the
 196 filled distribution relates to the conditional probability that the difference in means
 197 is greater than zero. We can see that xx/64 subgroup relationships have $p(\Delta > 0 | \text{data}) >$
 198 0.9.
 199

200 the symmetry-specific response (10) and to electrodes in an
 201 ROI over occipital cortex. When the same analysis was done
 202 using the odd harmonics from a parietal cortex ROI (Sup-
 203 plementary Figure 3.4) or using the even harmonics of the
 204 occipital cortex ROI (Supplementary Figure 3.4), the data was
 205 much less consistent with the subgroup relationships (yellow
 206 and green lines, Figure 4).

207 The current data provide a complete description of the
 208 visual system's response to symmetries in the 2-D plane. Our
 209 design does not allow us to independently measure the re-
 210 sponse to P1, but because each of the 16 other groups produce
 211 non-zero odd harmonic amplitudes (see Figure 1), we can con-
 212 clude that the relationships between P1 and all other groups,
 213 where P1 is the subgroup, are also preserved by the visual
 214 system. The subgroup relationships are not obvious perceptually,
 215 and most participants had no knowledge of group theory.
 216 Thus, the visual system's ability to preserve the subgroup
 217 hierarchy does not depend on explicit knowledge of the rela-
 218 tionships. Furthermore, behavioral experiments have shown
 219 that although naïve observers can distinguish many of the
 220 wallpaper groups (15), they are generally error-prone when
 221 asked to assign exemplar images to the appropriate group (16).
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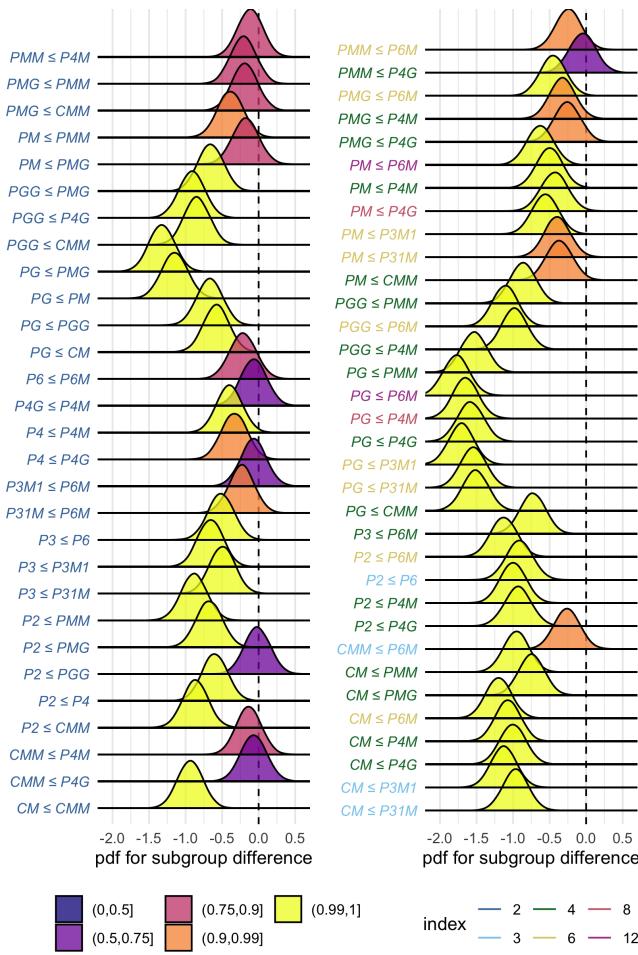


Fig. 3. Posterior distributions for the difference in mean display duration threshold. Colour coding of the text indicates the index of the subgroup, while the colour of the filled distribution relates to the conditional probability that the difference in means is greater than zero. We can see that $xx/64$ subgroup relationships have $p(\Delta|data) > 0.9$.

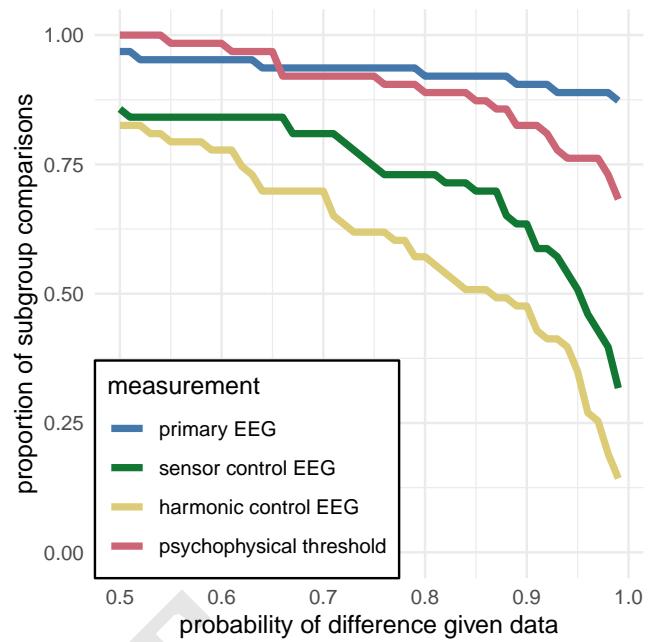


Fig. 4. This plot shows the proportion of subgroup relations that satisfy $p(\Delta > 0 | data) > x$. We can see that if we take $x = 0.95$ as our threshold, the subgroup relations are preserved in $56/63 = 89\%$ and $49/64 = 78\%$ of the comparisons for the primary EEG and display durations respectively. This compares to the $32/64 = 50\%$ and $22/64 = 35\%$ for the control EEG conditions.

when considering distortions due to perspective and occlusion. Near-regular textures, however abound in the visual world, and can be approximated as deformed versions of the wallpaper groups (24). The correspondence between brain data and group theory demonstrated here may indicate that the visual system represents visual textures using a similar scheme, with the wallpaper groups serving as anchor points in representational space. This framework resembles norm-based encoding strategies that have been proposed for other stimulus classes, most notably faces (25), and leads to the prediction that adaptation to wallpaper patterns should distort perception of near-regular textures, similar to the aftereffects found for faces (26). Field biologist have demonstrated that animals respond more strongly to exaggerated versions of a learned stimulus, referred to as “supernormal” stimuli (27). In the norm-based encoding framework, wallpaper groups can be considered super-textures, exaggerated examples of the near-regular textures that surround us. Artists may consciously or unconsciously create supernormal stimuli, to capture the essence of the subject and evoke strong responses in the audience (28). Wallpaper groups are visually compelling and have been widely used in human artistic expression going back to the Neolithic age (29). If wallpapers are super-textures, their prevalence may be a direct consequence of the strategy the human visual system uses for encoding visual textures.

Participants. Twenty-five participants (11 females, mean age 28.7 ± 13.3) took part in the EEG experiment. Their informed consent was obtained before the experiment under a protocol that was approved by the Institutional Review Board of Stanford University. 11 participants (8 females, mean age 20.73 ± 1.21) took part in the psychophysics experiment. All participants had normal or corrected-to-normal vision. Their

The correspondence between responses in the visual system and group theory that we demonstrate here, may reflect a form of implicit learning that depends on the structure of the natural world. The environment is itself constrained by physical forces underlying pattern formation and these forces are subject to multiple symmetry constraints (17). The ordered structure of responses to wallpaper groups could be driven by a central tenet of neural coding, that of efficiency. If coding is to be efficient, neural resources should be distributed in such a way that the structure of the environment is captured with minimum redundancy considering the visual geometric optics, the capabilities of the subsequent neural coding stages and the behavioral goals of the organism (18–21). Early work within the efficient coding framework suggested that natural images had a $1/f$ spectrum and that the corresponding redundancy between pixels in natural images could be coded efficiently with a sparse set of oriented filter responses, such as those present in the early visual pathway (22, 23). Our results suggest that the principle of efficient coding extends to a much higher level of structural redundancy – that of symmetries in visual images. The 17 wallpaper groups are completely regular, and relatively rare in the visual environment, especially

270 informed consent was obtained before the experiment under a
271 protocol that was approved by the University of Essex's Ethics
272 Committee.

273 **Stimulus Generation.** Exemplars from the different wallpaper
274 groups were generated using a modified version of the methodology
275 developed by Clarke and colleagues(16) that we have
276 described in detail elsewhere(10). Briefly, exemplar patterns
277 for each group were generated from random-noise textures,
278 which were then repeated and transformed to cover the plane,
279 according to the symmetry axes and geometric lattice specific
280 to each group. The use of noise textures as the starting
281 point for stimulus generation allowed the creation of an almost
282 infinite number of distinct exemplars of each wallpaper
283 group. For each exemplar image, phase-randomized control
284 exemplars were generated that had the same power spectrum
285 as the exemplar images for each group. The phase scrambling
286 eliminates rotation, reflection and glide-reflection symmetries
287 within each exemplar, but the phase-scrambled images inherent
288 the spectral periodicity arising from the periodic tiling.
289 This means that all control exemplars, regardless of which
290 wallpaper group they are derived from, degenerate to another
291 symmetry group, namely P1. P1 is the simplest of the wallpaper
292 groups, and contains only translations of a region whose
293 shape derives from the lattice. Because the different wallpaper
294 groups have different lattices, P1 controls matched to different
295 groups have different power spectra. Our experimental design
296 takes these differences into account by comparing the neural
297 responses evoked by each wallpaper group to responses evoked
298 by the matched control exemplars.

299 **Stimulus Presentation.** Stimulus Presentation. For the EEG
300 experiment, the stimuli were shown on a 24.5" Sony Trimaster
301 EL PVM-2541 organic light emitting diode (OLED) display
302 at a screen resolution of 1920×1080 pixels, 8-bit color depth
303 and a refresh rate of 60 Hz, viewed at a distance of 70 cm.
304 The mean luminance was 69.93 cd/m² and contrast was 95%.
305 The diameter of the circular aperture in which the wallpaper
306 pattern appeared was 13.8° of visual angle presented against
307 a mean luminance gray background. Stimulus presentation
308 was controlled using in-house software.

309 For the psychophysics experiment, the stimuli were shown
310 on a 48 × 27cm VIEWPixx/3D LCD Display monitor, model
311 VPX-VPX-2005C, resolution 1920×1080 pixels, with a viewing
312 distance of approximately 40cm and linear gamma. Stimulus
313 presentation was controlled using MatLab and Psychtoolbox-3
314 (30, 31). The diameter of the circular aperture for the stimuli
315 was 21.5°.

316 **EEG Procedure.** Visual Evoked Potentials were measured using
317 a steady-state design, in which P1 control images alternated
318 with test images from each of the 16 other wallpaper groups[2].
319 Exemplar images were always preceded by their matched P1
320 control image. A single 0.83 Hz stimulus cycle consisted of a
321 control P1 image followed by an exemplar image, each shown
322 for 600 ms. A trial consisted of 10 such cycles (12 sec) over
323 which 10 different exemplar images and matched controls from
324 the same rotation group were presented. For each group type,
325 the individual exemplar images were always shown in the same
326 order within the trials. Participants initiated each trial with
327 a button-press, which allowed them to take breaks between
328 trials. Trials from a single wallpaper group were presented

329 in blocks of four repetitions, which were themselves repeated
330 twice per session, and shown in random order within each
331 session. To control fixation, the participants were instructed
332 to fixate a small white cross in the center of display. To control
333 vigilance, a contrast dimming task was employed. Two times
334 per trial, an image pair was shown at reduced contrast, and the
335 participants were instructed to press a button on a response
336 pad. We adjusted the contrast reduction such that average
337 accuracy for each participant was kept at 85% correct, so that
338 the difficulty of the vigilance task was kept constant.
339

340 **Psychophysics Procedure.** The experiment consisted of 16
341 blocks, one for each of the wallpaper groups (excluding P1).
342 In each trial, participants were presented with two stimuli
343 (one of which was the wallpaper group for the current block of
344 trials, the other being P1), one after the other (inter stimuli
345 interval of 700ms). After each stimuli had been presented, it
346 was masked with white noise for 300ms. After both stimuli had
347 been presented, participants made a response on the keyboard
348 to indicate whether they thought the first or second contained
349 the most symmetry. Each block started with 10 practise trials,
350 (stimulus display duration of 500ms) to allow participants
351 to familiarise themselves with the current block's wallpaper
352 pattern. If they achieved an accuracy of 9/10 in these trials
353 they progressed to the rest of the block, otherwise they carried
354 out another set of 10 practise trials. This process was repeated
355 until the required accuracy of 9/10 was obtained. The rest of
356 the block consisted of four interleaved staircases (using the
357 QUEST algorithm (32), full details given in the SI) of 30 trials
358 each. On average, a block of trials took around 10 minutes to
359 complete.
360

361 **EEG Acquisition and Preprocessing.** Electroencephalogram
362 Acquisition and Preprocessing. The time-locked Steady-State
363 Visual Evoked Potentials were collected with 128-sensor HydroCell
364 Sensor Nets (Electrical Geodesics, Eugene, OR) and were band-pass
365 filtered from 0.3 to 50 Hz. Raw data were evaluated off line according to a sample-by-sample thresholding
366 procedure to remove noisy sensors that were replaced by the
367 average of the six nearest spatial neighbors. On average, less
368 than 5% of the electrodes were substituted; these electrodes
369 were mainly located near the forehead or the ears. The substitutions
370 can be expected to have a negligible impact on our results,
371 as the majority of our signal can be expected to come from
372 electrodes over occipital, temporal and parietal cortices.
373 After this operation, the waveforms were re-referenced to the
374 common average of all the sensors. The data from each 12s
375 trial were segmented into five 2.4 s long epochs (i.e., each
376 of these epochs was exactly 2 cycles of image modulation).
377 Epochs for which a large percentage of data samples exceeding
378 a noise threshold (depending on the participant and ranging
379 between 25 and 50 μ V) were excluded from the analysis on a
380 sensor-by-sensor basis. This was typically the case for epochs
381 containing artifacts, such as blinks or eye movements. The use
382 of steady-state stimulation drives cortical responses at specific
383 frequencies directly tied to the stimulus frequency. It is thus
384 appropriate to quantify these responses in terms of both phase
385 and amplitude. Therefore, a Fourier analysis was applied on
386 every remaining epoch using a discrete Fourier transform with
387 a rectangular window. The use of epochs two-cycles (i.e., 2.4
388 s) long, was motivated by the need to have a relatively high
389 resolution in the frequency domain, $\delta f = 0.42$ Hz. For each
390

frequency bin, the complex-valued Fourier coefficients were then averaged across all epochs within each trial. Each participant did two sessions of 8 trials per condition, which resulted in a total of 16 trials per condition.

SSVEP Analysis. Response waveforms were generated for each group by selective filtering in the frequency domain. For each participant, the average Fourier coefficients from the two sessions were averaged over trials and sessions. The Steady-State Visual Evoked Potentials (SSVEP) paradigm we used allowed us to separate symmetry-related responses from non-specific contrast transient responses. Previous work has demonstrated that symmetry-related responses are predominantly found in the odd harmonics of the stimulus frequency, whereas the even harmonics consist mainly of responses unrelated to symmetry, that arise from the contrast change associated with the appearance of the second image[2-4]. This functional distinction of the harmonics allowed us to generate a single-cycle waveform containing the response specific to symmetry, by filtering out the even harmonics in the spectral domain, and then back-transforming the remaining signal, consisting only of odd harmonics, into the time-domain. For our main analysis, we averaged the odd harmonic single-cycle waveforms within a six-electrode region of interest (ROI) over occipital cortex (electrodes 70, 74, 75, 81, 82, 83). These waveforms, averaged over participants, are shown in Figure 2 in the main paper. The same analysis was done for the even harmonics (see Figure S1) and for the odd harmonics within a six electrode ROI over parietal cortex (electrodes 53, 54, 61, 78, 79, 86; see Figure S2). The root-mean square values of these waveforms, for each individual participant, were used to determine whether each of the wallpaper subgroup relationships were preserved in the brain data.

Bayesian Analysis of EEG and Psychophysical data. Bayesian analysis was carried out using R (v3.6.1) (33) with the *brms* package (v2.9.0) (34) and rStan (v2.19.2 (35)). The data from each experiment were modelled using a Bayesian generalised mixed effect model with wallpaper group being treated as a 16 level factor, and random effects for participant. The EEG data and display thresholds were modelled using log-normal distributions with weakly informative, $\mathcal{N}(0, 2)$, priors. After fitting the model to the data, samples were drawn from the posterior distribution for each mean of the EEG response (display duration) for each wallpaper group. These samples were then recombined to calculate the distribution of differences for each pair of subgroup and super-group. These distributions were then summarised by computing the conditional probability of obtaining a positive (negative) difference, $p(\Delta|data)$.

For further technical details, please see the supplementary materials where the full R code, model specification, prior and posterior predictive checks, and model diagnostics, can be found.

snippets

Specifically, the amplitudes of symmetry-specific responses in individual participants ($n = 25$) preserve these relationships at an above-chance level in 88.3% (53 out of 60) of cases.

we used a steady-state design, in which exemplar images belonging to 16 of the 17 wallpaper groups alternated with phase-scrambled images of the same group. Exemplars from

each of the 16 groups alternated at 0.83 Hz with their corresponding set of P1 exemplars, that were matched in terms of their Fourier power spectrum.

Thus, the magnitude of the odd harmonic response components can be used as a distance metric for each group, with distance being measured relative to the simplest group, P1.

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1. Palmer SE (1985) The role of symmetry in shape perception. *Acta Psychologica* 59(1):67–90.
2. Cohen EH, Zaidi Q (2013) Symmetry in context: Salience of mirror symmetry in natural patterns. *Journal of vision* 13(6).
3. Li Y, Sawada T, Shi Y, Steinman R, Pizlo Z (2013) *Symmetry Is the sine qua non of Shape*, Advances in Computer Vision and Pattern Recognition, eds. Dickinson SJ, Pizlo Z. (Springer London), pp. 21–40.
4. Apthorpe D, Bell J (2015) Symmetry is less than meets the eye. *Current Biology* 25(7):R267–R268.
5. Fedorov E (1891) Symmetry in the plane in *Zapiski Imperatorskogo S. Peterburgskogo Mineralogicheskogo Obschestva [Proc. S. Peterb. Mineral. Soc.]*. Vol. 2, pp. 345–390.
6. Polya G (1924) XII. Über die analogie der kristallsymmetrie in der ebene. *Zeitschrift für Kristallographie-Crystalline Materials* 60(1):278–282.
7. Liu Y, Hel-Or H, Kaplan CS, Van Gool L (2010) Computational symmetry in computer vision and computer graphics. *Foundations and Trends® in Computer Graphics and Vision* 5(1–2):1–195.
8. Coxeter HSM, Moser WOJ (1972) *Generators and relations for discrete groups*, Ergebnisse der Mathematik und ihrer Grenzgebiete ; Bd. 14. (Springer-Verlag, Berlin, New York).
9. Möller AP (1992) Female swallow preference for symmetrical male sexual ornaments. *Nature* 357(6375):238–240.
10. Kohler PJ, Clarke A, Yakovleva A, Liu Y, Norcia AM (2016) Representation of maximally regular textures in human visual cortex. *The Journal of Neuroscience* 36(3):714–729.
11. Kohler PJ, Cottereau BR, Norcia AM (2018) Dynamics of perceptual decisions about symmetry in visual cortex. *NeuroImage* 167(Supplement C):316–330.
12. Norcia AM, Appelbaum LG, Ales JM, Cottereau BR, Rossion B (2015) The steady-state visual evoked potential in vision research: A review. *Journal of Vision* 15(6):4–4.
13. Norcia AM, Candy TR, Petett MW, Vildavski VY, Tyler CW (2002) Temporal dynamics of the human response to symmetry. *Journal of Vision* 2(2):132–139.
14. Sasaki Y, Vanduffel W, Knutson T, Tyler C, Tootell R (2005) Symmetry activates extrastriate visual cortex in human and nonhuman primates. *Proceedings of the National Academy of Sciences of the United States of America* 102(8):3159–3163.
15. Landwehr K (2009) Camouflaged symmetry. *Perception* 38:1712–1720.
16. Clarke ADF, Green PR, Halley F, Chantler MJ (2011) Similar symmetries: The role of wallpaper groups in perceptual texture similarity. *Symmetry* 3(4):246–264.
17. Hoyle RB (2006) *Pattern formation: an introduction to methods*. (Cambridge University Press).
18. Attreave F (1954) Some informational aspects of visual perception. *Psychol Rev* 61(3):183–93.
19. Barlow HB (1961) *Possible principles underlying the transformations of sensory messages*, ed. Rosenblith WA. (MIT Press), pp. 217–234.
20. Laughlin S (1981) A simple coding procedure enhances a neuron's information capacity. *Z Naturforsch C* 36(9–10):910–2.
21. Geisler WS, Najemnik J, Ing AD (2009) Optimal stimulus encoders for natural tasks. *Journal of Vision* 9(13):17–17.
22. Field DJ (1987) Relations between the statistics of natural images and the response properties of cortical cells. *J Opt Soc Am A* 4(12):2379–94.
23. Olshausen BA, Field DJ (1997) Sparse coding with an overcomplete basis set: a strategy employed by v1? *Vision Res* 37(23):3311–25.
24. Liu Y, Lin WC, Hays J (year?) Near-regular texture analysis and manipulation in *ACM Transactions on Graphics (TOG)*. (ACM), Vol. 23, pp. 368–376.
25. Leopold DA, Bondar IV, Giese MA (2006) Norm-based face encoding by single neurons in the monkey inferotemporal cortex. *Nature* 442(7102):572–5.
26. Webster MA, MacLin OH (1999) Figural aftereffects in the perception of faces. *Psychon Bull Rev* 6(4):647–53.
27. Tinbergen N (1953) *The herring gull's world: a study of the social behaviour of birds*. (Frederick A. Praeger, Inc., Oxford, England), pp. xvi, 255.
28. Ramachandran VS, Hirstein W (1999) The science of art: A neurological theory of aesthetic experience. *Journal of Consciousness Studies* 6(6–7):15–41.
29. Jablan SV (2014) *Ornament and Modularity*. (World Scientific Publishing Co Pte Ltd, Singapore, SINGAPORE).
30. Kleiner M, et al. (2007) What's new in psychtoolbox-3. *Perception* 36:1–16.
31. Brainard DH (1997) Spatial vision. *The psychophysics toolbox* 10:433–436.
32. Watson AB, Pelli DG (1983) Quest: A bayesian adaptive psychometric method. *Perception & psychophysics* 33(2):113–120.
33. R Core Team (2019) *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna, Austria).
34. Bürkner PC (2017) Advanced bayesian multilevel modeling with the r package brms. *arXiv preprint arXiv:1705.11123*.
35. Stan Development Team (2019) RStan: the R interface to Stan. R package version 2.19.2.