

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

Peter J. Kohler^{a, b, 1} and Alasdair D. F. Clarke^c

^aYork University, Department of Psychology, Toronto, ON M3J 1P3, Canada; ^bCentre for Vision Research, York University, Toronto, ON, M3J 1P3, Canada; ^cStanford University, Department of Psychology, Stanford, CA 94305, United States; ^dUniversity of Essex, Department of Psychology, Colchester, UK, CO4 3SQ

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1 A century of vision research has demonstrated that symmetry con-
2 tributes to numerous domains of visual perception (1–4). In a 2-D
3 image, the four fundamental symmetries, reflection, rotation, transla-
4 tion and glide reflection, can be combined in 17 distinct ways. These
5 17 “wallpaper” groups (5–7) obey a hierarchy, determined by mathe-
6 matical group theory, in which simpler groups are subgroups of more
7 complex ones(8). Here we probe representations of symmetries in
8 wallpaper groups using two methods: (1) Steady-State Visual Evoked
9 Potentials (SSVEPs) recorded using EEG and (2) symmetry detection
10 thresholds measured psychophysically. We find that hierarchical re-
11 lationships between the wallpaper groups are almost perfectly pre-
12 served in both behavior and response amplitudes in visual cortex.
13 This remarkable consistency between the structure of symmetry rep-
14 resentations and mathematical group theory, is likely generated over
15 visual development, through implicit learning of regularities in the
16 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 atten-
10 tion 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 data
22 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

another, the inner group is called a subgroup of the outer group (7). Subgroup relationships between wallpaper groups can be distinguished by their indices. The index of a subgroup relationship is the number of cosets, i.e. the number of times 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).

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

Significance Statement

Wallpaper groups were discovered in the mid-19th century, and the 17 groups constitute the complete set of possible ways of regularly tiling the 2D-plane. In recent years wallpaper groups have found use in the vision science community, as an ideal stimulus set for studying the perception of symmetries in textures. Here we present brain imaging and psychophysical data on the complete set of wallpaper groups and show the hierarchical organization among wallpaper groups in reflected in both representations in visual cortex and performance on a symmetry detection task. This shows that the visual system is highly sensitive to regularities in textures, and suggest that symmetries may play an important role in texture perception.

PJK and ADFC designed the study, PJK collected EEG data, ADFC collected psychophysical data, PJK and ADFC wrote the paper.

The authors have no conflicts of interests to declare

¹To whom correspondence should be addressed. E-mail: pjohler@yorku.ca

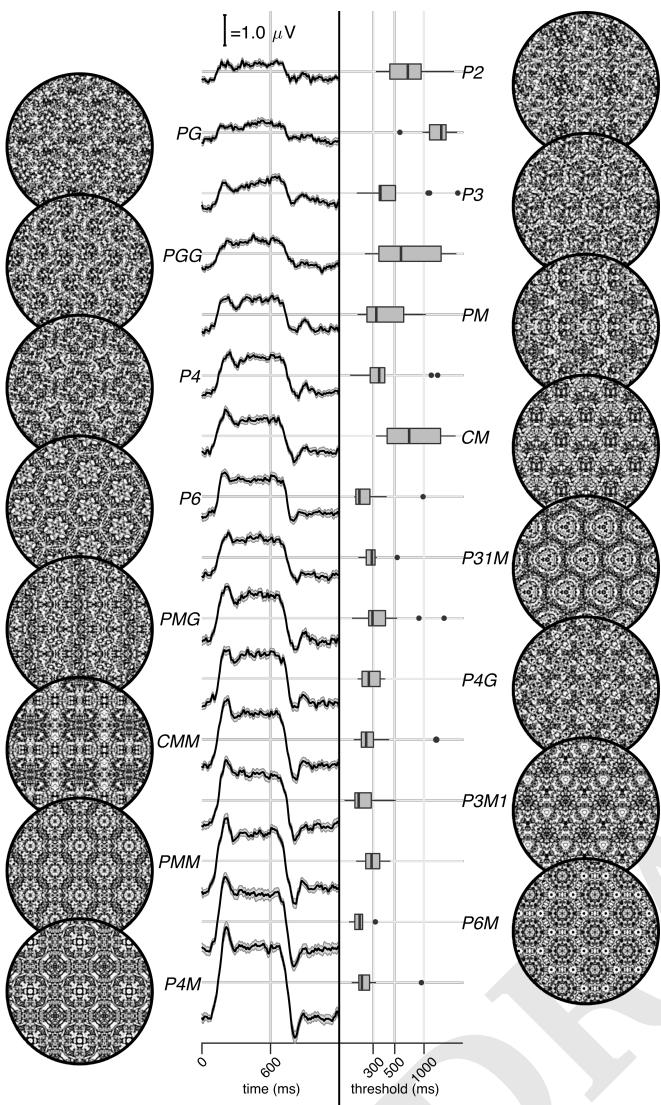


Fig. 1. Exemplar stimulus for each of the 16 wallpaper groups, with corresponding <something EEG> and a boxplot showing the distribution of display duration thresholds.

Results

The stimuli used in our two experiments were multiple exemplar 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 exemplar images. Because all wallpapers are periodic due to their lattice tiling structure, the phase-scrambled images all belong 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 threshold duration could be computed for each wallpaper group.

A summary of our results can be seen in Figure 1 ...

Discussion

Here we show that beyond merely responding to the elementary symmetry operations of reflection (14) and rotation (10), the visual system explicitly represents hierarchical structure of the 17 wallpaper groups, and thus the compositions of all four of the fundamental symmetry transformations (rotation, reflection, translation, glide reflection) which comprise regular textures. The RMS measure of SSVEP amplitude, preserves the complex hierarchy of subgroup relationships among the wallpaper groups (8). Out of a total of 60 relationships, 53 were preserved in a significant number of participants, and 49 were significant even at a stricter threshold ($p < 0.002$). The ordering was highly stable in individual participants, with an average preservation rate of 21 of 25 participants across all 60 relationships (see Figure 3). This remarkable consistency was specific to the odd harmonics of the stimulus frequency, that capture the symmetry-specific response (10) and to electrodes in an ROI over occipital cortex. When the same analysis was done on the even harmonics of the occipital cortex ROI, the ordering of responses was much less apparent (see Figure S2) and preservation rates much lower (see Figure S4). The odd harmonics from electrodes in an ROI over parietal cortex, showed even weaker evidence of preserving the hierarchy among subgroups (see Figure S5). Importantly, no relationships were preserved in either of these control analyses that were not also preserved in the main analysis of the odd harmonics in the occipital cortex ROI. The current data provide a complete description of the visual system's response to symmetries in the 2-D plane. Our design does not allow us to independently measure the response to P1, but because each of the 16 other groups produce non-zero odd harmonic amplitudes (see Figure 2), we can conclude that the relationships between P1 and all other groups, where P1 is the subgroup, are also preserved by the visual system. The subgroup relationships are not obvious perceptually, and most participants had no knowledge of group theory. Thus, the visual system's ability to preserve the subgroup hierarchy does not depend on explicit knowledge of the relationships. Furthermore, behavioral experiments have shown that although naïve observers can distinguish many of the wallpaper groups (15), they are generally error-prone when asked to assign exemplar images to the appropriate group (16). The correspondence between responses in the visual system

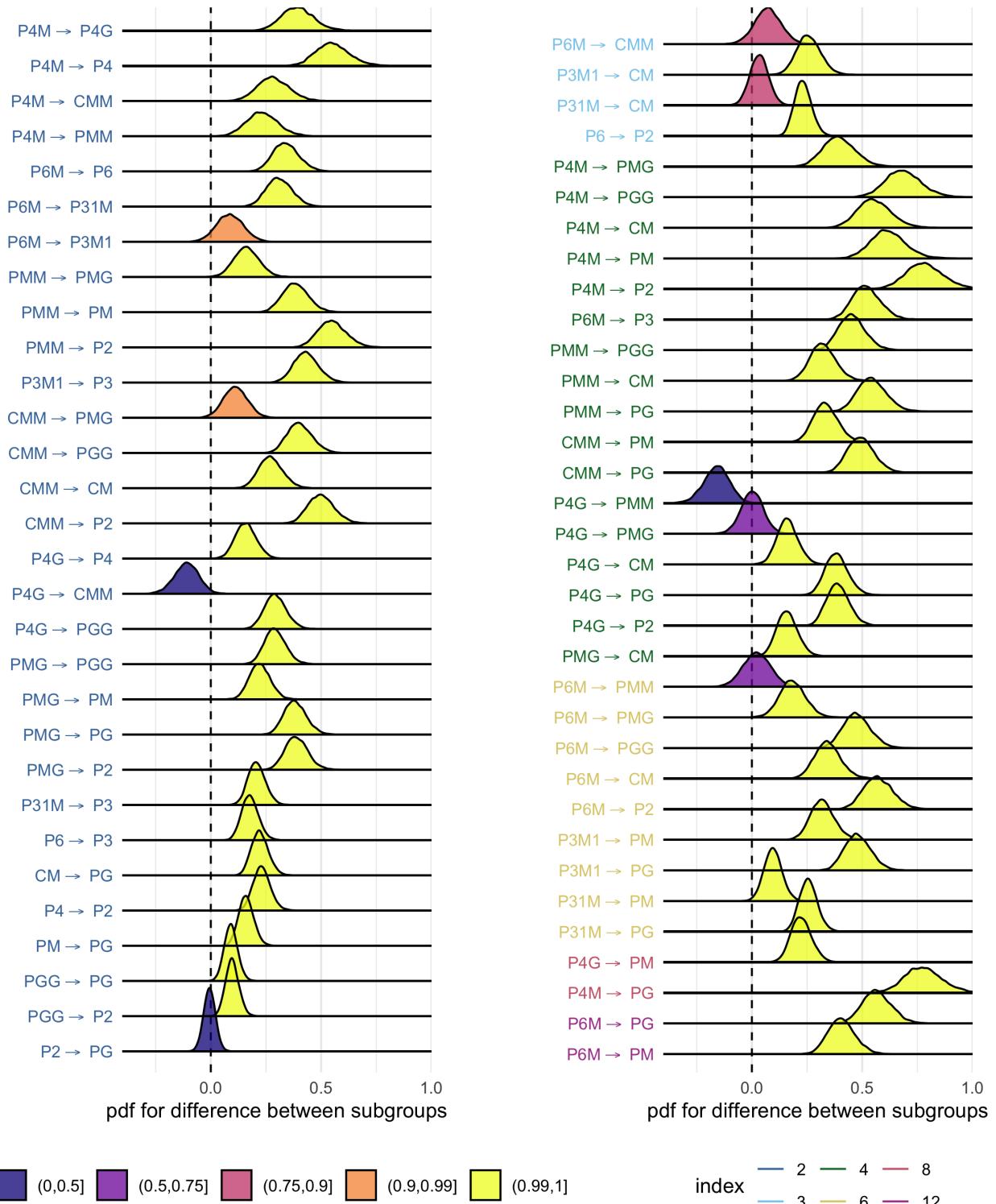


Fig. 2. Posterior distributions for the difference in mean RMS EEG response. Colour coding of the text indicates the index of the subgroup, while the colour of the filled distribution relates to the conditional probability that the difference in means is greater than zero. We can see that 55/64 subgroup relationships have $p(\Delta|data) > 0.9$.

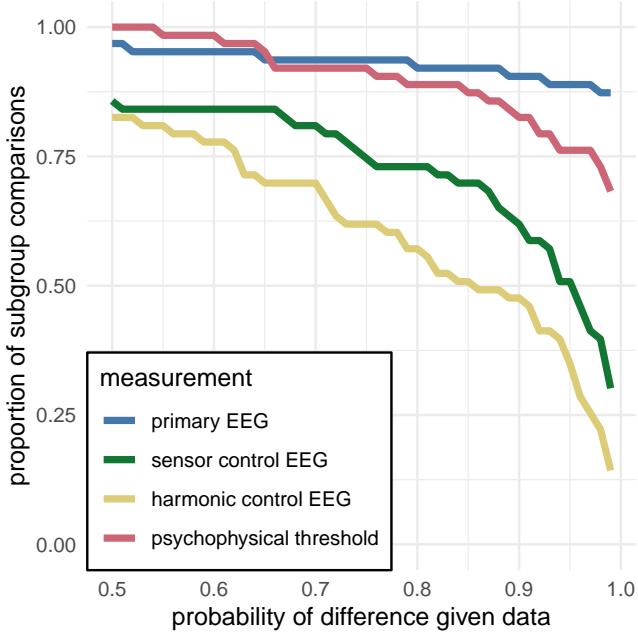


Fig. 3. Posterior distributions for the difference in mean RMS EEG response. Colour coding of the text indicates the index of the subgroup, while the colour of the filled distribution relates to the conditional probability that the difference in means is greater than zero. We can see that 55/64 subgroup relationships have $p(\Delta|data) > 0.9$.

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 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.

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.

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

Stimulus Generation. Exemplars from the different wallpaper groups were generated using a modified version of the methodology developed by Clarke and colleagues (16) that we have described in detail elsewhere (10). Briefly, exemplar patterns for each group were generated from random-noise textures, which were then repeated and transformed to cover the plane, according to the symmetry axes and geometric lattice specific to each group. The use of noise textures as the starting point for stimulus generation allowed the creation of an almost infinite number of distinct exemplars of each wallpaper group. For each exemplar image, phase-randomized control exemplars were generated that had the same power spectrum as the exemplar images for each group. The phase scrambling eliminates rotation, reflection and glide-reflection symmetries within each exemplar, but the phase-scrambled images inherit the spectral periodicity arising from the periodic tiling. This means that all control exemplars, regardless of which wallpaper group they are derived from, degenerate to another symmetry group, namely P1. P1 is the simplest of the wallpaper groups, and contains only translations of a region whose shape derives from the lattice. Because the different wallpaper groups have different lattices, P1 controls matched to different

230 groups have different power spectra. Our experimental design
231 takes these differences into account by comparing the neural
232 responses evoked by each wallpaper group to responses evoked
233 by the matched control exemplars.

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

244 For the psychophysics experiment, the stimuli were shown
245 on a 48 × 27cm VIEWPixx/3D LCD Display monitor, model
246 VPX-VPX-2005C, resolution 1920×1080 pixels, with a viewing
247 distance of approximately 40cm and linear gamma. Stimulus
248 presentation was controlled using MatLab and Psychtoolbox-3
249 (30, 31). The diameter of the circular aperture for the stimuli
250 was 21.5°.

251 **EEG Procedure.** Visual Evoked Potentials were measured using
252 a steady-state design, in which P1 control images alternated
253 with test images from each of the 16 other wallpaper groups[2].
254 Exemplar images were always preceded by their matched P1
255 control image. A single 0.83 Hz stimulus cycle consisted of a
256 control P1 image followed by an exemplar image, each shown
257 for 600 ms. A trial consisted of 10 such cycles (12 sec) over
258 which 10 different exemplar images and matched controls from
259 the same rotation group were presented. For each group type,
260 the individual exemplar images were always shown in the same
261 order within the trials. Participants initiated each trial with
262 a button-press, which allowed them to take breaks between
263 trials. Trials from a single wallpaper group were presented
264 in blocks of four repetitions, which were themselves repeated
265 twice per session, and shown in random order within each
266 session. To control fixation, the participants were instructed
267 to fixate a small white cross in the center of display. To control
268 vigilance, a contrast dimming task was employed. Two times
269 per trial, an image pair was shown at reduced contrast, and the
270 participants were instructed to press a button on a response
271 pad. We adjusted the contrast reduction such that average
272 accuracy for each participant was kept at 85% correct, so that
273 the difficulty of the vigilance task was kept constant.

274 **Psychophysics Procedure.** The experiment consisted of 16
275 blocks, one for each of the wallpaper groups (excluding P1).
276 In each trial, participants were presented with two stimuli
277 (one of which was the wallpaper group for the current block of
278 trials, the other being P1), one after the other (inter stimuli
279 interval of 700ms). After each stimuli had been presented, it
280 was masked with white noise for 300ms. After both stimuli had
281 been presented, participants made a response on the keyboard
282 to indicate whether they thought the first or second contained
283 the most symmetry. Each block started with 10 practise trials,
284 (stimulus display duration of 500ms) to allow participants
285 to familiarise themselves with the current block's wallpaper
286 pattern. If they achieved an accuracy of 9/10 in these trials
287 they progressed to the rest of the block, otherwise they carried
288 out another set of 10 practise trials. This process was repeated

289 until the required accuracy of 9/10 was obtained. The rest of
290 the block consisted of four interleaved staircases (using the
291 QUEST algorithm (32), full details given in the SI) of 30 trials
292 each. On average, a block of trials took around 10 minutes to
293 complete.

294 **EEG Acquisition and Preprocessing.** Electroencephalogram
295 Acquisition and Preprocessing. The time-locked Steady-State
296 Visual Evoked Potentials were collected with 128-sensor HydroCell
297 Sensor Nets (Electrical Geodesics, Eugene, OR) and were band-pass
298 filtered from 0.3 to 50 Hz. Raw data were evaluated off line according to a sample-by-sample thresholding
299 procedure to remove noisy sensors that were replaced by the
300 average of the six nearest spatial neighbors. On average, less
301 than 5% of the electrodes were substituted; these electrodes
302 were mainly located near the forehead or the ears. The substitutions
303 can be expected to have a negligible impact on our results,
304 as the majority of our signal can be expected to come
305 from electrodes over occipital, temporal and parietal cortices.
306 After this operation, the waveforms were re-referenced to the
307 common average of all the sensors. The data from each 12s
308 trial were segmented into five 2.4 s long epochs (i.e., each
309 of these epochs was exactly 2 cycles of image modulation).
310 Epochs for which a large percentage of data samples exceeding
311 a noise threshold (depending on the participant and ranging
312 between 25 and 50 μ V) were excluded from the analysis on a
313 sensor-by-sensor basis. This was typically the case for epochs
314 containing artifacts, such as blinks or eye movements. The use
315 of steady-state stimulation drives cortical responses at specific
316 frequencies directly tied to the stimulus frequency. It is thus
317 appropriate to quantify these responses in terms of both phase
318 and amplitude. Therefore, a Fourier analysis was applied on
319 every remaining epoch using a discrete Fourier transform with
320 a rectangular window. The use of epochs two-cycles (i.e., 2.4
321 s) long, was motivated by the need to have a relatively high
322 resolution in the frequency domain, $\delta f = 0.42$ Hz. For each
323 frequency bin, the complex-valued Fourier coefficients were
324 then averaged across all epochs within each trial. Each participant
325 did two sessions of 8 trials per condition, which resulted
326 in a total of 16 trials per condition.

327 **EEG Analysis.** Response waveforms were generated for each
328 group by selective filtering in the frequency domain. For each
329 participant, the average Fourier coefficients from the two ses-
330 sions were averaged over trials and sessions. The Steady-State
331 Visual Evoked Potentials paradigm we used allowed us to sep-
332 arate symmetry-related responses from non-specific contrast
333 transient responses. Previous work has demonstrated that
334 symmetry-related responses are predominantly found in the
335 odd harmonics of the stimulus frequency, whereas the even
336 harmonics consist mainly of responses unrelated to symme-
337 try, that arise from the contrast change associated with the
338 appearance of the second image[2-4]. This functional distinc-
339 tion of the harmonics allowed us to generate a single-cycle
340 waveform containing the response specific to symmetry, by
341 filtering out the even harmonics in the spectral domain, and
342 then back-transforming the remaining signal, consisting only of
343 odd harmonics, into the time-domain. For our main analysis,
344 we averaged the odd harmonic single-cycle waveforms within
345 a six-electrode region of interest (ROI) over occipital cortex
346 (electrodes 70, 74, 75, 81, 82, 83). These waveforms, averaged
347 over participants, are shown in Figure 2 in the main paper.

- 349 The same analysis was done for the even harmonics (see Figure 420
 350 S1) and for the odd harmonics within a six electrode ROI over 421
 351 parietal cortex (electrodes 53, 54, 61, 78, 79, 86; see Figure 422
 352 S2). The root-mean square values of these waveforms, for each 423
 353 individual participant, were used to determine whether each 424
 354 of the wallpaper subgroup relationships were preserved in the 425
 355 brain data.
- 356 **Bayesian Analysis of EEG and Psychophysical data.** Bayesian 426
 357 analysis was carried out using R (v3.6.1) (33) with the brms 427
 358 package (v2.9.0) (34) and rStan (v2.19.2 (35)). The data from 428
 359 each experiment were modelled using a Bayesian generalised 429
 360 mixed effect model with wallpaper group being treated as a 430
 361 16 level factor, and random effects for participant. The EEG 431
 362 data and display thresholds were modelled using log-normal 432
 363 distributions with weakly informative, $\mathcal{N}(0, 2)$, priors. After 433
 364 fitting the model to the data, samples were drawn from the pos- 434
 365 terior distribution for each mean of the EEG response (display 435
 366 duration) for each wallpaper group. These samples were then 436
 367 recombined to calculate the distribution of differences for each 437
 368 pair of subgroup and super-group. These distributions were 438
 369 then summarised by computing the conditional probability of 439
 370 obtaining a positive (negative) difference, $p(\Delta|data)$.
- 371 For further technical details, please see the supplementary 440
 372 materials where the full R code, model specification, prior and 441
 373 posterior predictive checks, and model diagnostics, can be 442
 374 found.
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 376 here, set in a single paragraph. Please do not include any acknowl- 444
 377 edgments in the Supporting Information, or anywhere else in the 445
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