Brain Responses to Symmetries in Naturalistic Novel Three-Dimensional Objects

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Abstract

Human brains are sensitive to symmetry, especially vertical reflection, which is present in human faces and many other biological forms. However, symmetries in most visual scenes are rotated relative to the observer's viewing location, failing to produce symmetry in the retinal image. We investigated the differences between perspective-distorted symmetry, and images that produce symmetry on the retina, and measured the association between responses to symmetry and autism spectrum disorder (ASD). We found that perspective-distorted symmetry with cues to 3D shape elicited responses, and both image-level and perspective distorted 3D symmetry elicited stronger responses than 2D symmetry. 3D image-level symmetry created stronger responses than 3D perspective-distorted symmetry. Lastly, there was no association between responses to symmetry and ASD. We conclude that symmetry processing occurs in the absence of a symmetry-related task, even for perspective-distorted symmetry. Additionally, there may not be any association between conditions that affect global processing and symmetry processing.

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1. Introduction

1.1 Perceptual organization

The visual system (eyes and brain) processes visual information, such as shape and color. It is able to organize disparate parts of a scene into something that appears as a coherent whole (Treder, 2010). This process is referred to as perceptual organization. Perceptual organization occurs for all senses (sight, sound, touch, smell, and taste), but is often studied in the context of vision (Wagemans, 2018). The process of understanding the physical world visually can be broken down into three levels: low level vision (encoding of basic image features in a scene (Peirce, 2015)), mid-level vision (explicit and coherent encoding of shapes and surfaces in the environment), and high-level vision (recognition, categorization and interpretation of objects) (Anderson, 2020). Perceptual organization is often used synonymously with mid-level vision, because it is understood as the stage between the processing of low-level information about the basic properties of visual stimuli (edges, spatial frequency, colors, contrast, etc.) and the higher order semantic interpretation of that information (faces, scenes, objects, etc.) (Peirce, 2015). Features such as form, complex texture, and depth cues, and processes such as spatial integration are processed in mid-level vision. Low-level properties are combined in mid-level vision to accomplish object recognition, figure and ground segmentation, grouping, and recovering three-dimensional (3D) representations of objects and scenes for further, higher order visual processing. Gestalt properties are part of perceptual organization/mid-level vision (Bertamini et al., 2018).

1.2 Gestalt psychology

Gestalt psychologists began to study perceptual organization in the twentieth century. Gestalt theory identified several principles that describe how perceptual organization takes place, including: symmetry and order, figure and ground, similarity, closure, proximity, and continuation (Kubovy, 1981). Each of these properties occur as a result of grouping and segregation operations of visual stimuli, and allows for holistic representations of what would otherwise be interpreted as separate, fragmented visual

elements (Koffka, 1935). This thesis focuses on the neural mechanisms underlying a specific aspect of perceptual organization – symmetry perception.

1.3 The significance of vertical reflection for perception

Different types of symmetry (reflection, translation, rotation, and glide reflection) are found in the visual environment (Treder, 2010). However, reflection symmetry (symmetry where patterns are mirrored over one or more axes) is the most easily detected form of symmetry by the human visual system (Bertamini et al., 1997; Bertamini & Makin, 2014), especially when reflection symmetry axes are vertical (Dakin & Hess, 1997; Wenderoth, 1994).

Objects and scenes with reflection symmetry over a single vertical axis (also called bilateral symmetry) is especially prevalent in both natural and man-made scenes and objects (Washburn, 1999). Many living animals and plants tend to have at least one form of symmetry, and many portray vertical symmetry specifically (Treder, 2010). For example, a butterfly would be an example of a bilaterally symmetric animal (one reflection symmetry axis). In addition to there being evolutionary pressures towards producing symmetrical objects in nature, symmetric structures may preferentially arise because the process of producing symmetry is more easily integrated into genetic code (Johnston et al., 2022).

Furthermore, symmetry has been used in man-made structures in architecture and art for centuries (Mehaffy & Salingaros, 2021), and there is evidence that human observers prefer symmetry both in faces and abstract patterns (Makin et al., 2012; Rhodes et al., 1998). This would suggest that in addition to having visual systems that are highly sensitive to symmetry, humans also have an aesthetic preference for symmetry. Understanding the mechanisms that moderate symmetry perception can guide the development of more effective graphic designs, architectural structures, computer interfaces, object recognition technologies, aesthetic projects, and face recognition technology.

1.4 Symmetry as a cue to object and scene perception

Visual environments are complex, and the ability to segregate objects is essential for making meaningful interpretations of a scene. The understanding of symmetry as a gestalt principle of perceptual organization suggests that the brain continuously detects

symmetries in the visual input, and uses them as a cue to object and scene perception (Treder, 2010). There is evidence to suggest that symmetries are quickly detected, and help us recognize and categorize objects in the environment (Treder, 2010). Symmetry processing contributes to an object formation process known as figure-ground segmentation (Driver et al., 1992). Human observers have a tendency towards perceiving symmetrical objects as a whole figure. Perhaps this is because the presence of a symmetrical element in a visual scene indicates the presence of a single object that is distinct from the rest of the scene. This is because it is rare for symmetry to result from random or accidental properties (Treder, 2010), and because it is distinct and stands out from a background (Parovel & Vezzani, 2002). Specifically, Parovel & Vezzani (2002) found that objects with vertical or horizontal mirror symmetry and multiple axes of symmetry are more likely to be perceived as a single object.

If symmetry is to contribute to object perception and figure ground segmentation, then it has to be continuous, quick and automatic. (Kimchi & Peterson, 2008). Symmetry perception is thought to be automatic, as it occurs soon after stimulus onset in (Anzai et al., 2007), and even when a task is not symmetry related (Koning & Wagemans, 2009). In accordance with gestalt principles, symmetry gives structure to visual stimuli, even when the image seems abstract (Kubovy, 1981). Sasaki et al. (2005) showed that symmetry-related brain regions are activated when symmetry is present in the visual field, even when the task at hand is not symmetry related. The results suggest that symmetry is still processed, and can serve as a cue to visual processing, even when attention is not directed towards symmetries in the stimulus. However, in a functional magnetic resonance imaging (fMRI) study, Keefe et al., (2018) found that attention to symmetry causes an increase in symmetry responses. While there was measurable symmetry processing when participants engaged in a conflicting task, responses were more robust for symmetry related tasks. Keefe (2018) explains that this difference in results may be due to the capability of fMRI to detect attentional effects, as task dependence is not reflected in the results of electroencephalogram (EEG) studies of symmetry (Höfel & Jacobsen, 2007; Makin et al., 2014; Norcia et al., 2002; Rampone et al., 2014; Wright et al., 2017).

1.5 The human visual system

The visual cortex is a part of the cerebral cortex, and its purpose is to process visual stimuli in the external world (Huff et al., 2023). Photoreceptors in the retina convert light received from the external world into electrical signals that travel to the visual cortex through the lateral geniculate nucleus (LGN) (Weyand, 2016). This information is first received in the primary visual cortex area V1, where elements such as orientation, spatial frequency, and direction of moving stimuli are initially processed (Hallum et al., 2011; Huff et al., 2023). The V1 area is responsible for the earliest processing of visual information, and is the foundation for more complex pattern recognition to occur in later visual areas (Huff et al., 2023). From there, information from V1 is further processed in area V2, which responds better to more complex stimuli such as motion. The visual cortex divides to form two separate pathways: the ventral stream, which is involved with recognition of shapes and objects, and the dorsal stream, which processes information pertaining to spatial location, shape, orientation, motion, speed and visual attention (Hebart & Hesselmann, 2012). Notably, a third pathway that is specialized for aspects of social perception has been proposed and is growing in acceptance. This pathway begins in the early visual cortex and extends into the superior temporal sulcus through motion selective areas (Pitcher & Ungerleider, 2021).

Neuroimaging studies show that the human visual system is sensitive to symmetry. Symmetry processing presumably occurs predominantly in the ventral stream. Specifically, areas V3, V3A, V4d/v, V7, lateral occipital complex (LOC) and ventral occipital VO1 are sensitive to symmetry (Keefe et al., 2018; Kohler et al., 2016; Sasaki et al., 2005; Tyler et al., 2005). Furthermore, there is a well characterized event related potential (ERP) called the sustained posterior negative (SPN) component that is associated with the presence of symmetry (Jacobsen & Höfel, 2003).

1.6 Perspective-distortion

While symmetry is often present in natural visual scenes, symmetry in the world does not always lead to symmetry on the retina. Image-level symmetry refers to the 2D retinal projection of a 3D object (Treder, 2010). Image-level symmetry on the retina is

quite rare. During natural vision, symmetries in the visual scene are often rotated in various directions relative to the observer's viewing location, such that they fail to produce symmetry in the retinal image, due to perspective-distortion. In order to detect whether or not a perspective-distorted object is symmetrical, the brain needs to recover a 3D representation of that object and account for the perspective-distortion. fMRI studies show that image-level symmetry creates stronger brain responses than perspective-distorted symmetry when manipulating the role of task by directing symmetry toward and away from symmetry (Keefe et al., 2018), and EEG studies using ERPs have found that distorted symmetry creates symmetry responses only when participants engage in symmetry-related tasks (Makin et al., 2015).

In the brain imaging literature previously mentioned (Keefe et al., 2018; Makin et al., 2015), symmetrical dot patterns were used as stimuli, however, when biological images such as animal silhouettes are used, symmetry detection is more efficient than for dot patterns (Evans et al., 2000). While images of animals more closely approximate objects that are found in real world settings, the images were 2D and had image-level symmetry. This does not address the question of how symmetry can be a cue to 3D scene and object representations when symmetry detection itself requires recovering 3D representations of the scene/object. Since most of what humans view in day-to-day scenes and objects are rich and naturalistic, we may be able to better understand this problem by using different stimuli. There is a growing interest in understanding how perspective-distorted symmetry is processed. Most of the work on perspective-distorted symmetry is based on dot patterns (Keefe et al., 2018; Makin et al., 2016; Sasaki et al., 2005). We were interested in using more naturalistic stimuli. In the current study, we did so by comparing brain responses to procedurally generated novel, naturalistic, 3D objects under two viewing conditions: image-level and perspective-distorted symmetry. We define "naturalistic" as the characteristic of being closely approximated to objects observed during natural viewing, as opposed to dot pattern arrays, which are commonly used in studies of symmetry processing. Our images have cues to three-dimensional shape (shading), as do objects present in natural viewing. For example, these objects may resemble real objects such as popcorn, or pebbles on a beach. An additional experiment used the same paradigm, with 2D versions of the original 3D images. The

second experiment allows us to test whether the 3D versions generate a stronger response to image-level symmetry, and to ensure that responses to perspective-distorted symmetry are in fact driven by shading cues to 3D in the objects.

This study addressed several gaps in our current understanding of symmetry perception. We used high-density EEG with steady-state visual evoked potentials (SSVEPs); a methodology (Norcia et al., 2015) which has not previously been used to study perspective-distorted symmetry. SSVEPs is a paradigm for measuring brain activity that occurs in response to visual stimuli that are presented periodically. Our SSVEP paradigm makes it possible to isolate the symmetry-specific brain responses that are associated with a visual stimulus by focusing on the odd harmonics of a stimulation frequency. Additionally, we used stimuli (naturalistic, novel 3D objects) that have not previously been used to study perspective-distorted symmetry perception. These stimuli and paradigm produced results that differed from previous work with perspective-distortions.

Lastly, there are only a handful of studies that explore the association between brain responses to symmetry and developmental conditions that affect global processing, such as autism-spectrum disorder (ASD). Perreault et al. (2011) found that people with and without ASD were able to detect mirror symmetry along vertical axes better than horizontal and oblique axes, however, those with ASD were more sensitive to symmetry across all orientations. As an exploratory component of the main study, we correlated responses to symmetry, measured using the SSVEP technique as described above, to traits associated with ASD using the Autism Spectrum Quotient (AQ). In the current study, we expand on the previous work by directly correlating brain responses to symmetry with AQ scores.

We aimed to address the following three research questions: (1) Will perspective-distorted symmetry in naturalistic, novel 3D objects generate a symmetry response in the brain using an SSVEP paradigm? (2) How will whole scalp topographies and response amplitudes differ between image-level and perspective-distorted symmetry? (3) Is there a relationship between AQ results and perspective-distorted and image-plane symmetry perception?

2. Methods

2.1 Participants

Fifty-four adults participated in one or both of the EEG experiments (age range 18 to 54 years; mean 22.59, SD = 8.00. 38 female). Six participated in both, 24 participated only in the 3D experiment, and 24 participated in only the 2D experiment. Visual acuity was tested with a Snellen chart, ensuring that all participants had normal or corrected-to-normal vision, with a visual acuity no worse than 20/32. Participants wore correction during visual acuity testing and during the experiment. Upon arrival, participants received a detailed explanation of the EEG acquisition procedure, the potential risks (such as infection if there are open wounds on the scalp), their right to stop the experiment and withdraw at any time, and the parameters of data confidentiality. Participants then read and signed an informed consent form as well a participant survey. The participant survey was used to collect health information such as sex, age, history of brain injury and neurological concerns, etc. Participants who had visual acuity below -0.5 or had a history of neurological illness would be rejected. The protocol has been approved by the Office of Research Ethics at York University. Participants were recruited primarily from the York University Undergraduate Research Participant Pool. Additional participants were recruited by other methods, such as word of mouth.

2.2 Stimuli

Symmetrical and asymmetrical objects were generated procedurally using *Blender* (a graphics software), and a Python script that generates unique objects that either do or do not have a vertical axis of reflection symmetry. 3D and 2D symmetrical and asymmetrical objects were generated for this study (see Figure 1). The 3D objects were created by placing a total of 14 “Metaballs” at 3 different locations from an object center, using 3 different radii (larger Metaballs near the center of the object). Metaballs are spherical structures that will morph together when positioned in close proximity. The distances, radii, and the number of balls were the same for all objects. The ball locations were randomly selected, but there were always an equal number of balls at each distance on either side of the object’s vertical axis. When placed like this, the Metaballs combine to create asymmetrical objects. In order to impose reflection symmetry on an object, the

same coordinates on each side of an object were used, but the horizontal axis was flipped so that balls with same distance were placed at the same y and z location on each side of the object. The algorithm was used to produce 200 asymmetrical and 200 symmetrical objects. Each object was rendered in greyscale under two viewing conditions, (1) with the camera positioned facing the x-axis, such that reflection symmetry is present in the image-plane, and (2) with the camera positioned on the right side of the object, but still pointing towards the center of the object and maintaining the same distance from the object center as in viewing condition 1. This meant that the object was rotated relative to the camera so that no symmetry is present in the image-plane. This was done for both asymmetrical and symmetrical objects, however, while rotation eliminates symmetry in the image-plane for the symmetrical objects, it does not have a noticeable effect on the general appearance of the asymmetrical objects. 200 symmetry images and 200 no-symmetry images were created. Image-level and perspective-distorted versions were created for both.

All 2D images were created by eliminating the shading found in the original 3D images such that no depth cues were present in the resulting image. Pixel values were averaged across the object contour, and the average value assigned to each pixel inside the contour. This resulted in a similar shade for each object, that differed only slightly from image to image.

The 3D Experiment consisted of three basic conditions: (a) symmetrical vs asymmetrical, (b) asymmetrical vs asymmetrical, (c) symmetrical vs symmetrical. Symmetrical vs symmetrical data was collected but not further analyzed in the current study. The same four image sets were used for all three conditions (asymmetrical 01, asymmetrical 02, symmetrical 01, and symmetrical 02). This image pairing procedure was done separately for both the image-level and perspective-distorted conditions.

We started with 200 images, which were then taken through an artificial neural network (ANN) based selection process to select 10 image pairs per condition. To control for low-level differences between two matched images, we selected pairs of images for each condition that created similar activations in the ANN, which was trained on object image classification, VGG-16 (Simonyan & Zisserman, 2015). Specifically, we made sure that the activations elicited by the two images in the first fully connected layer in the

network had a correlation of 0.45±0.01. This procedure ensures that across conditions, each image pair is equally well-matched in terms of low to mid-level visual features. Any differences among conditions can be reasonably attributed to the symmetry content of the images.

In addition to the 3D objects, we used two groups of 2D images. The first group was simply 2D versions of the 3D images previously described (referred to as “matched 2D group”). The second group was an additional set of 2D images that were unrelated to the original 3D images, chosen based on a separate ANN selection process run on the 2D images (referred to as “ANN 2D group”). Conditions were again based on distinct combinations of the same four image sets (asymmetrical 01, asymmetrical 02, symmetrical 01, and symmetrical 02).

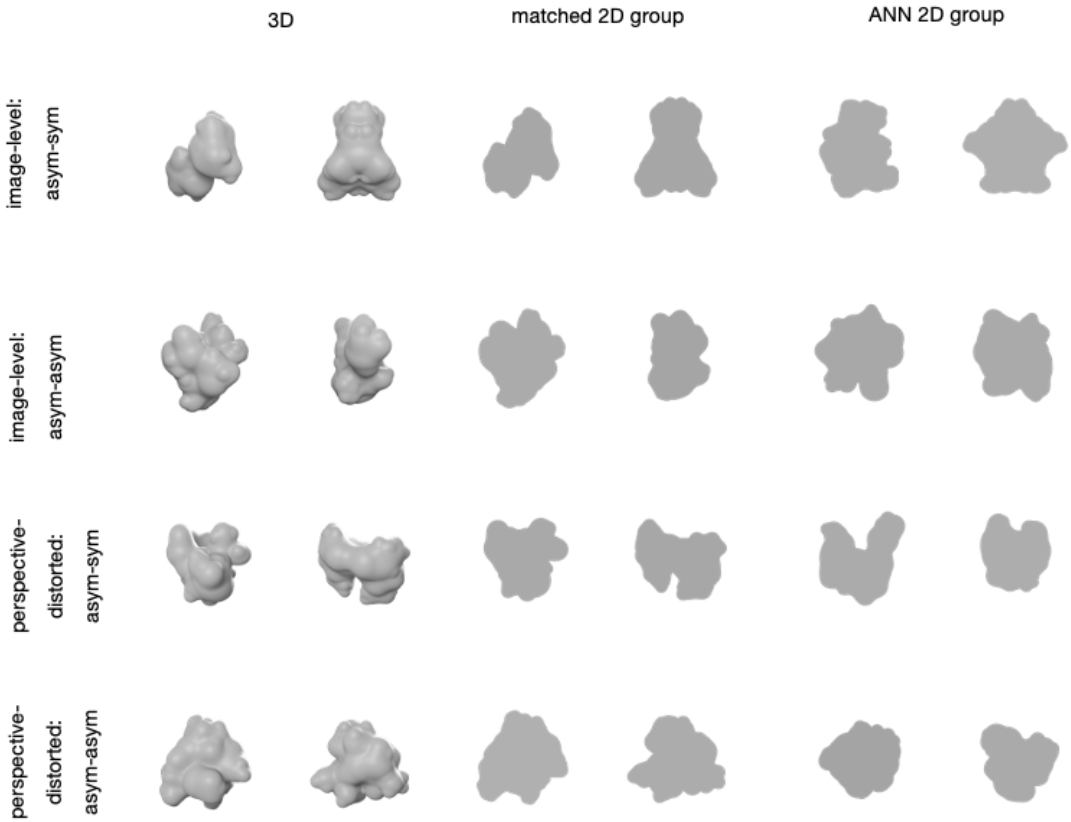

Figure 1 Examples of stimuli used in the two Experiments. Column one displays the 3D stimuli used in Experiment 1. Column two displays 2D versions of the 3D images used in Experiment 1 without cues to 3D shape. Column three displays the additional set of 2D images chosen based on a separate artificial neural network (ANN) selection process. Stimuli displayed in columns two and three were used in Experiment 2.

2.3 Experiment Design

In Experiment 1, participants passively viewed images of 3D, naturalistic, novel objects centered on a screen. The viewing distance was 105cm. In each trial, 10 pairs of images were shown sequentially, with each image shown for 500 milliseconds (ms). Each image pair formed a single stimulus cycle of 1 second duration, for a stimulation frequency of 1 Hz. The total trial duration was 10 seconds, and the image pair exemplars were always shown in the same order, for each condition. The result was 6 conditions with 25 trials per condition (5 trials per condition in each block for a total of 5 blocks), for a total of 150 trials in the entire experiment. Importantly, across these 6 conditions, all image pairs were matched for mid-level image properties using the ANN procedure described above.

In Experiment 2, participants passively viewed the two groups of 2D images previously described. Each of these two groups had the same conditions as Experiment 1, except that the two symmetry-symmetry conditions were not included in these experiments. This resulted in 8 conditions with 20 trials per condition (4 trials per condition in each block for a total of 5 blocks) for a total of 160 trials in the entire Experiment.

In both Experiments, participants viewed the stimuli on a 24.5-inch screen (Dell P2417H) with a 1920 x 1080 pixel resolution. The visual angle was 12º and the refresh rate was 60 Hz. EEG was recorded with 128 sensor HydroCell Sensor Nets (Electrical Geodesics, Eugene, OR). EEG recording time was approximately 30-40 minutes (not including short breaks between blocks) for both experiments.

All participants completed the AQ following the EEG recording session. The AQ is a self-administered 50 question Likert scale survey (a 4-point scale ranging from definitely agree to definitely disagree) used to assess 5 categories of autism traits in adults with or without ASD (Baron-Cohen et al., 2001). The categories include social skills, attention switching, attention to detail, communication, and imagination (see Appendix A). Baron-Cohen et al., (2001) showed that the AQ has good test-retest and interrater reliability and strong correlation with clinical assessments of ASD. Although ASD assessment is most accurately done through clinical diagnosis, this was not feasible for our exploratory study, and the AQ is a commonly used self-administered questionnaire-based alternative that

can be used as one component of assessment (Woodbury-Smith et al., 2005). A score above 29 is the proposed cut off, indicating notable traits of autism.

2.4 Analysis

Raw data from noisy sensors were replaced by the average of the six nearest non-noisy sensors (Kohler et al., 2016). 20% of bad channels were removed. Noisy sensors tended to be located near the forehead, jaw, and ears. Participants were rejected from analyses if more than 50% of trials were rejected across electrodes in any condition. Based on this criterion, 2 participants from Experiment 1 (3D) and 2 participants from Experiment 2 (2D) were rejected from further analyses after data collection due to too many trials/electrodes rejected due to artifacts. This resulted in 28 participants' data being included in further analyses for both experiments. The first and last cycles of both experiments (i.e., the prelude and postlude) were excluded from the analysis, so the analyzed dataset consisted of 8 1-second stimulus cycles.

A harmonic is a frequency component that is a multiple of a fundamental frequency (Norcia et al., 2015). Odd harmonics are the frequency components that are odd multiples of a frequency, while even harmonics are even multiples of a frequency. In SSVEP data, even harmonics, by definition, will capture responses that are identical for the first and second half of the stimulation cycle. In our SSVEP paradigm, this means that low-level image-update responses, that do not vary systematically between the first and second image in each cycle, will be captured by the even harmonics. Odd harmonics, on the other hand, reflect responses that are distinct between the first and the second image. Our ANN-based image matching procedure ensured that for all conditions in our experiments, image pairs were equally well-matched except for symmetry, so odd harmonics will primarily capture responses to symmetry (Kohler et al., 2016). Specially, any differences in odd harmonics between asymmetrical-symmetrical and asymmetrical-asymmetrical conditions can be used as a measure of the symmetry response. We will refer to the asymmetrical-symmetrical conditions as test conditions, and the asymmetrical-asymmetrical conditions as control conditions. We expect to see a symmetry response in the test condition, but not in the control condition.

SSVEP data were first averaged in the time-domain to create single-cycle averages. We then used a Fourier transform to convert the data from the time domain to

the frequency domain. We analyzed data from the first and second harmonics in three electrode regions-of-interest (ROIs) over the occipital cortex and the left and right temporal cortices. ROIs were defined based on independent data from a previous experiment that was identical to the current experiment, but where the images were accidentally mismatched across image pairs. Average amplitudes across trials, ROI electrodes and participants were calculated using coherent averaging, in which the real and imaginary components are averaged independently. We calculated the projected amplitudes for each participant by finding the average phase and amplitude across participants using coherent averaging of different components, and then projecting each participant's vector onto the group vector average. Vector averages are computed separately for each harmonic in the dataset. Projected amplitudes served as independent samples for each participant, that could be used for computing the standard error and for statistical analysis. The projection procedure is useful because projection takes phase variability into account with associated signal to noise ratio improvements that would not occur if amplitude averages and corresponding statistical tests were simply computed from individual participant amplitudes. We used a linear mixed model to test for the presence of any relationships between projected amplitudes and each condition in each ROI. As described above, we expect symmetry responses to be isolated in the odd harmonics, while the even harmonics will capture more generic, low-level image processing. Therefore, our statistical analysis was done using the amplitudes of the first harmonic (1f1). We used projected amplitude of 1f1 as the dependent variable, and ROI (occipital, left temporal and right temporal regions), symmetry (whether an image was symmetric or asymmetric) and view (whether an image was distorted by perspective) as fixed effects, with participants as a random effect. For those experiments where we found significant main effects and interactions, we also ran post-hoc t-tests comparing the asymmetry-symmetry (test) and asymmetry-asymmetry (control) conditions within each stimulus type (image-level and perspective-distorted symmetry, 3D and 2D).

An electrode-by-electrode Hotelling's T^2 test was performed to compare control (asymmetric vs asymmetric) and test (asymmetric vs symmetric) conditions. This test is useful because it is a version of a paired t-test that can take the real and imaginary

components of the response into account, and thus incorporate both phase and amplitude. Comparing real and imaginary values of the responses between test and control conditions at each electrode eliminated the restriction of comparing the average projected amplitudes of multiple electrodes within an ROI. This allowed us to identify whether there was a significant difference between test and control conditions at specific electrode points.

Finally, we used a Pearson correlation coefficient to determine whether there was a relationship between projected amplitudes (from the test conditions for image-level and perspective-distorted stimuli) and AQ scores in the 3D data set for all ROIs.

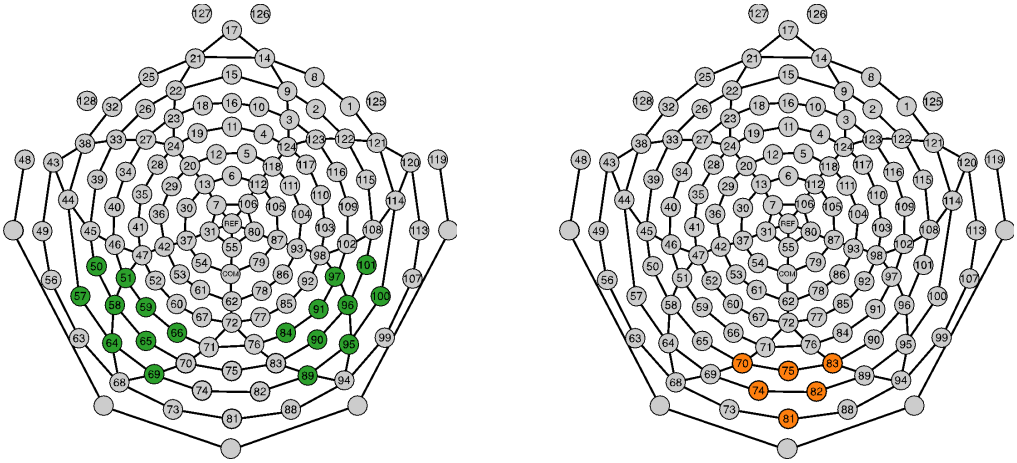

Figure 2 Map of electrode ROIs in the occipital, left temporal and right temporal regions. ROIs were defined based on independent data from a previous experiment.

3. Results

We first present data from the second harmonic (2f1). As mentioned above, we did not conduct any statistical tests on the second harmonic for any of the experiments, but as predicted, the topographies (see Figures 3 to 5) and ROI analyses (see Figures 6 to 8) are broadly similar across conditions within each experiment.

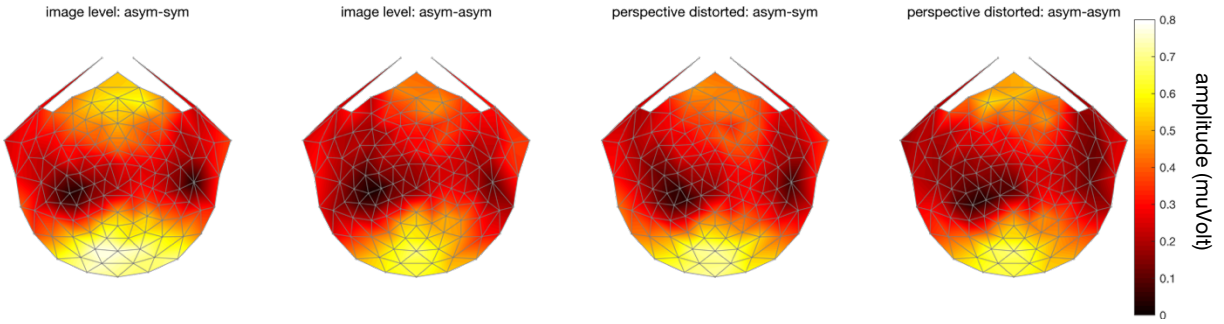

Figure 3 Second harmonic topographies, Experiment 1 (3D). Whole-scalp topographies based on the coherent average of the second harmonic (2f1) of individual participant amplitudes in Experiment 1 (3D). The topographies and amplitudes of responses were broadly similar among all conditions.

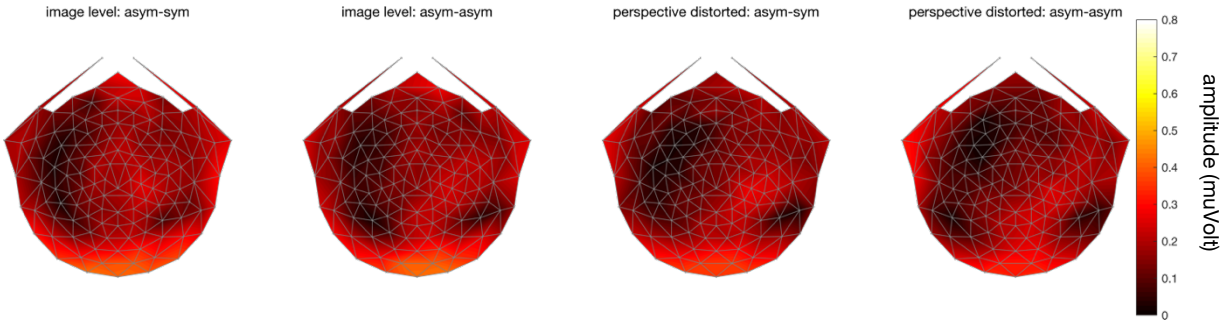

Figure 4 Second harmonic topographies, Experiment 2 (2D) (ANN 2D group). Whole-scalp topographies based on the coherent average of the second harmonic (2f1) of individual participant amplitudes in Experiment 2 (2D) (ANN 2D group). The topographies and amplitudes of responses were broadly similar among all conditions.

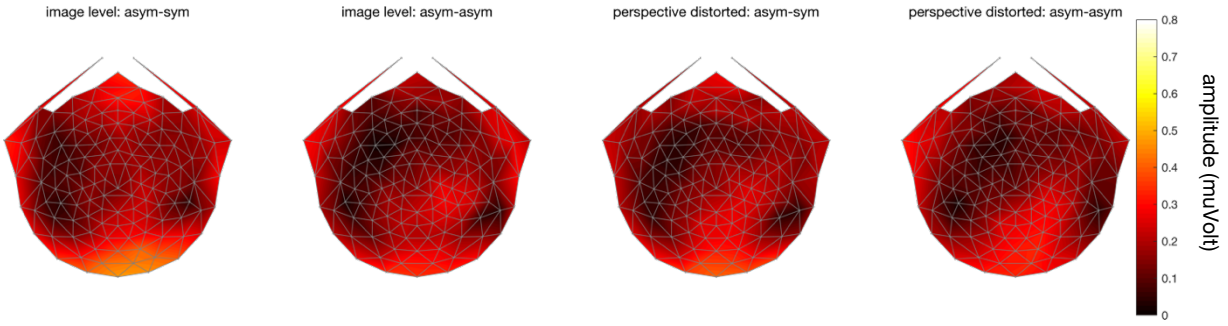

Figure 5 Second harmonic topographies, Experiment 2 (2D) (matched 2D group). Whole-scalp topographies based on the coherent average of the second harmonics (2f1) of individual participant amplitudes in Experiment 2 (2D) (matched 2D group). The topographies and amplitudes of responses were broadly similar among all conditions.

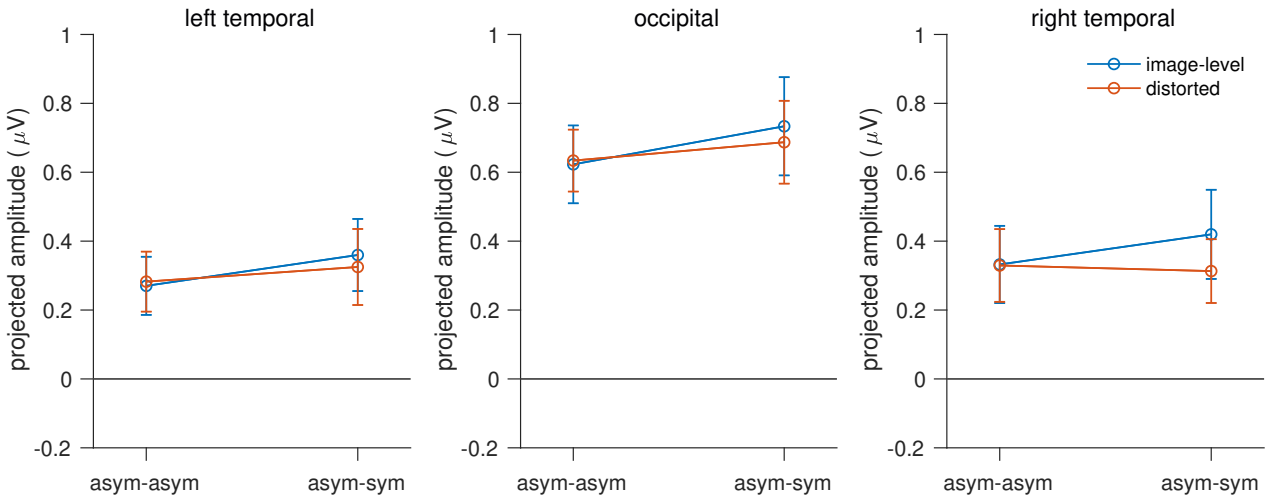

Figure 6 Second harmonic ROI analysis, Experiment 1 (3D). ROI analysis comparing projected amplitudes in control (asymmetric and asymmetric) and test (asymmetric and symmetric) conditions in the second harmonic (2f1) of the stimulation frequency in Experiment 1 (3D). The straight line displayed in this image indicates where zero is.

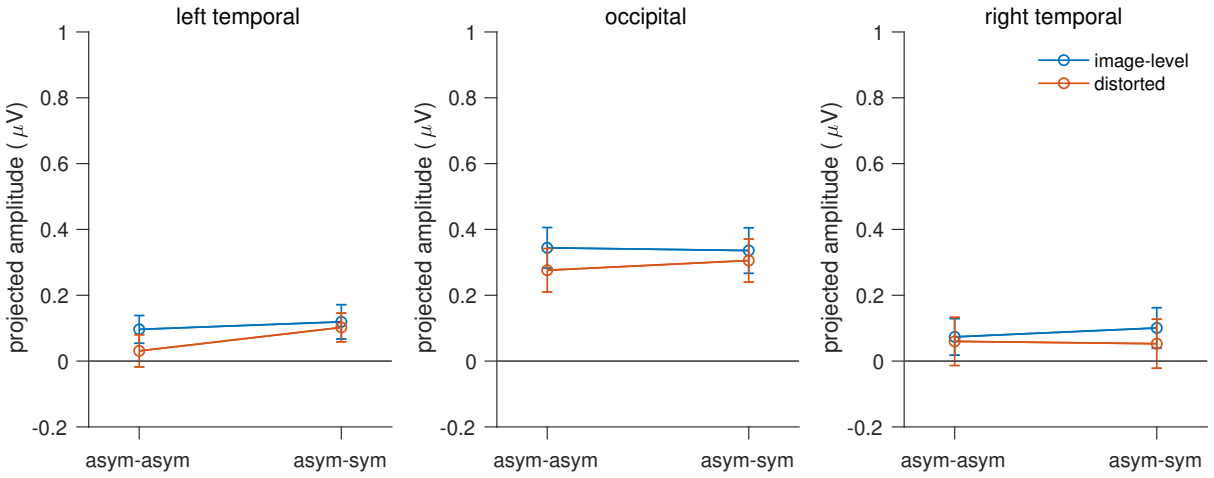

Figure 7 Second harmonic ROI analysis, Experiment 2 (2D) (ANN 2D group). ROI analysis comparing projected amplitudes in control (asymmetric and asymmetric) and test (asymmetric and symmetric) conditions in the second harmonic (2f1) of the stimulation frequency in Experiment 2 (2D) (ANN 2D group). The straight line displayed in this image indicates where zero is.

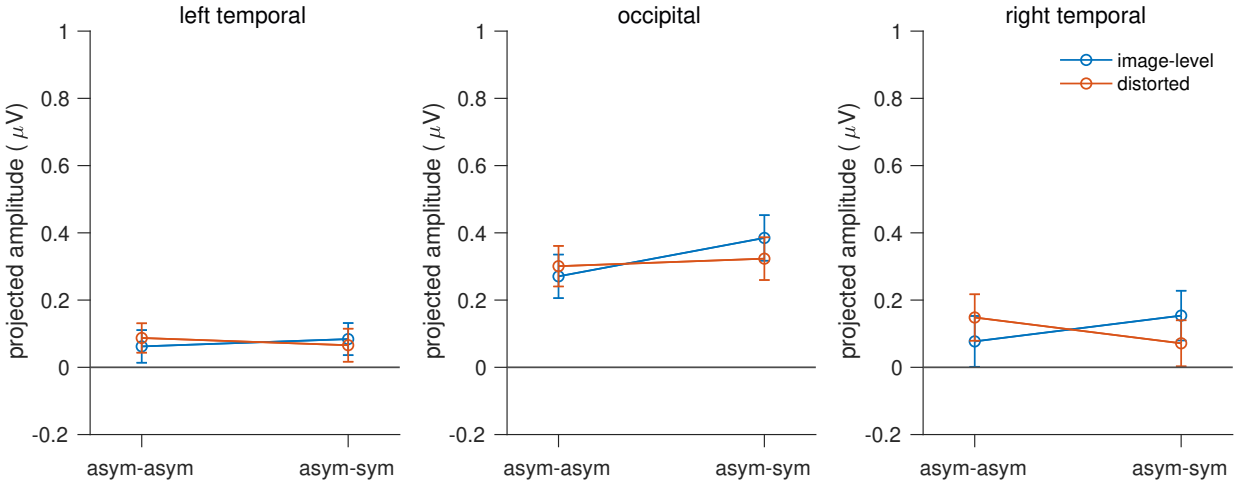

Figure 8 Second harmonic ROI analysis, Experiment 2 (2D) (matched 2D group). ROI analysis comparing projected amplitudes in control (asymmetric and asymmetric) and test (asymmetric and symmetric) conditions in the second harmonic (2f1) of the stimulation frequency in Experiment 2 (2D) (matched 2D group). The straight line displayed in this image indicates where zero is.

We now present the data from the first harmonic (1f1), starting with Experiment 1, which used the 3D versions of the naturalistic novel objects. Within the 3D data set, there was a significant main effect of symmetry $F(1, 27.03) = 15.93$, $p < 0.001$. There was also a significant two-way interaction between symmetry factor and view factor $F(1, 27.12) = 5.30$, $p = 0.029$. There were no other main effects or interactions. Post hoc t-tests examining individual effects showed the following results for the image-level 3D stimuli: There was a significant difference between the test and control conditions in the occipital ROI, $t(27) = -4.35$, $p < 0.001$, the left temporal ROI, $t(27) = -5.68$, $p < 0.001$, as well as the right temporal ROI, $t(27) = -7.41$, $p < 0.001$. Post hoc t-tests examining individual effects showed the following results for the perspective-distorted 3D stimuli: There was a significant difference between the test and control conditions in the occipital ROI, $t(27) = -2.28$, $p = 0.030$, the left temporal ROI, $t(27) = -2.60$, $p = 0.015$, as well as the right temporal ROI, $t(27) = -2.87$, $p = 0.008$. These results indicate that the odd harmonic responses are different between the test and control conditions, and that this difference is mediated by view, consistent with the idea that the odd harmonic captures symmetry responses that are influenced by perspective-distortion. Although there was no interaction with ROI, we did generally see larger effects for the right temporal ROI compared to the occipital and left temporal (see Figure 10).

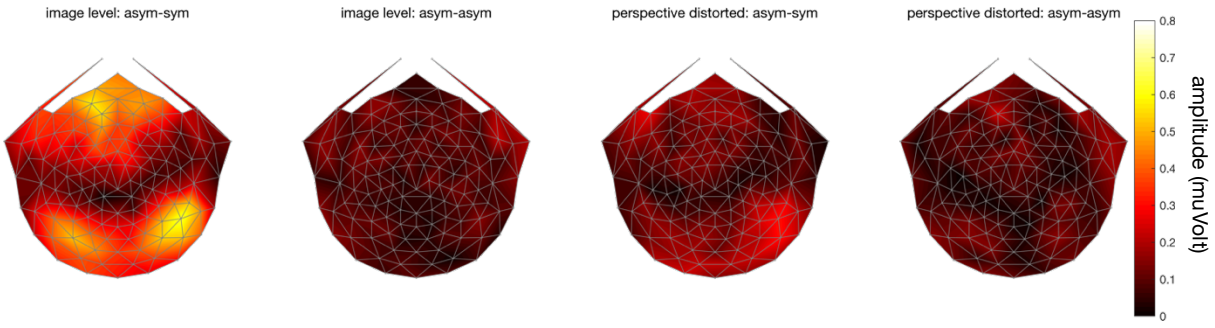

Figure 9 First harmonic topographies, Experiment 1 (3D). Whole-scalp topographies based on the coherent average of the first harmonic (1f1) of individual participant amplitudes in Experiment 1 (3D). The symmetry response can be observed as the difference between the topographies produced by the test conditions (asymmetric and symmetric) and the control conditions (asymmetric and asymmetric).

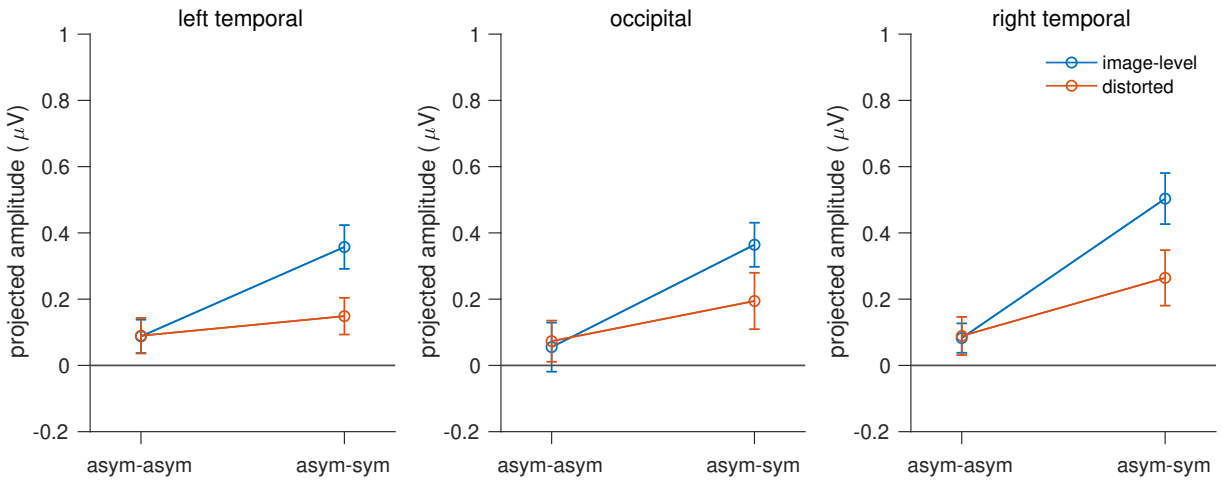

Figure 10 First harmonic ROI analysis, Experiment 1 (3D). ROI analysis comparing projected amplitudes in control (asymmetric and asymmetric) and test (asymmetric and symmetric) conditions in the first harmonic (1f1) of the stimulation frequency in Experiment 1 (3D). The straight line displayed in this image indicates where zero is.

We now present the data from the first harmonic (1f1) from the first four conditions of Experiment 2 (see Figures 11 and 12), which used a different set of 2D images, matched using an ANN with the same approach as Experiment 1. Within the 2D ANN data set, there were significant main effects of ROI $F(2, 30.04) = 3.30$, $p = 0.051$ and view factor $F(1, 27.10) = 8.22$, $p = 0.008$. There was one significant three way interaction between ROI, symmetry factor and view factor $F(2, 100.64) = 4.07$, $p = 0.020$. There were no other main effects or interactions. Post hoc t-tests examining the individual effects showed that there was a significant difference between test and control conditions in the right temporal ROI for the image-level stimuli, $t(27) = -2.21$, $p = 0.036$. There were no significant differences between test and control conditions in any of the three ROIs for the perspective-distorted stimuli. These results indicate that the odd harmonic responses are different between the test and control conditions only in the right temporal ROI and only for image-level stimuli.

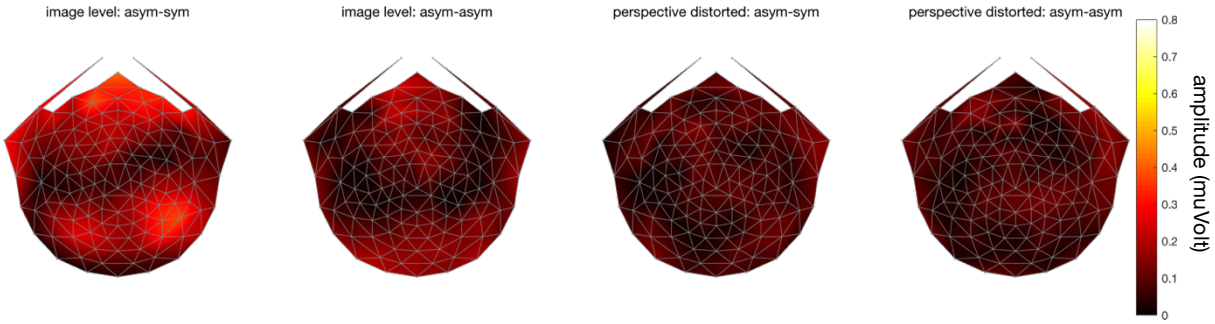

Figure 11 First harmonic topographies, Experiment 2 (2D) (ANN 2D group). Whole-scalp topographies based on the coherent average of the first harmonic (1f1) of individual participant amplitudes in Experiment 2 (2D) (ANN 2D group). The symmetry response can be observed as the difference between the topographies produced by the test conditions (asymmetric and symmetric) and the control conditions (asymmetric and asymmetric).

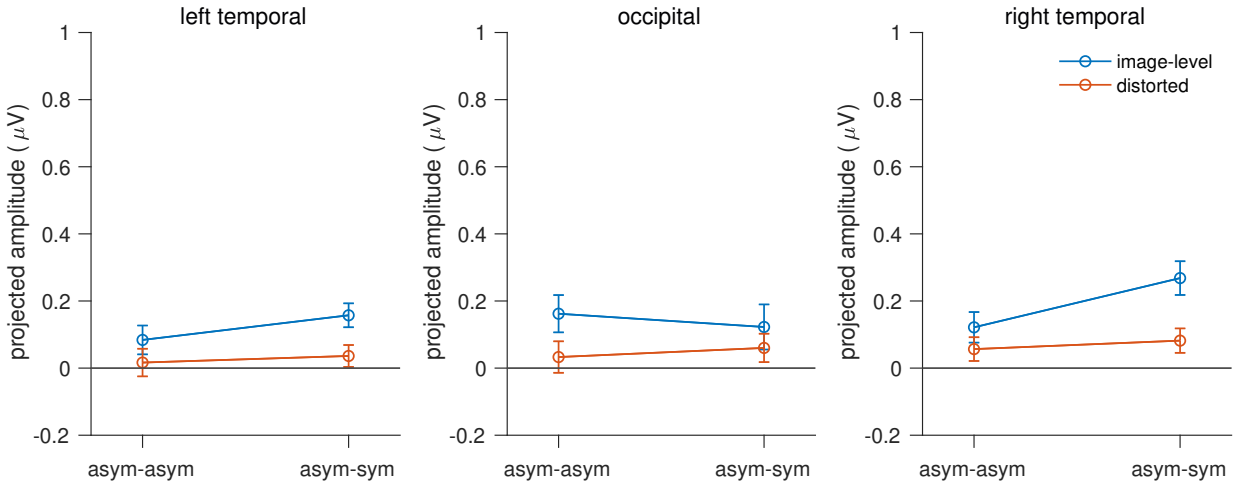

Figure 12 First harmonic ROI analysis, Experiment 2 (2D) (ANN 2D group). ROI analysis comparing projected amplitudes in control (asymmetric and asymmetric) and test (asymmetric and symmetric) conditions in the first harmonic (1f1) of the stimulation frequency in Experiment 2 (2D) (ANN 2D group). The straight line displayed in this image indicates where zero is.

We now present the data from the first harmonic (1f1) from the last four conditions of Experiment 2 (see Figures 13 and 14), which used 2D versions of the exact same images used in Experiment 1. Within the 2D matched data set, there was a significant main effect of symmetry factor $F(1, 27.57) = 13.41$, $p = 0.001$. There were no

other main effects or interactions. Post hoc t-tests examining individual effects showed the following results for the image-level 2D stimuli: There was a significant difference between the test and control conditions in the occipital ROI, t(27) = -2.52, p = 0.018, the left temporal ROI, t(27) = -2.72, p = 0.011, and the right temporal ROI t(27) = -3.45, p = 0.002. There were no significant differences between test and control conditions in any of the three ROIs for the perspective-distorted 2D stimuli. The lack of an interaction with view is surprising, because it suggests that there is a measurable symmetry response to the perspective-distorted stimuli, even in the absence of shading cues to 3D shape. We will discuss this further in the next section.

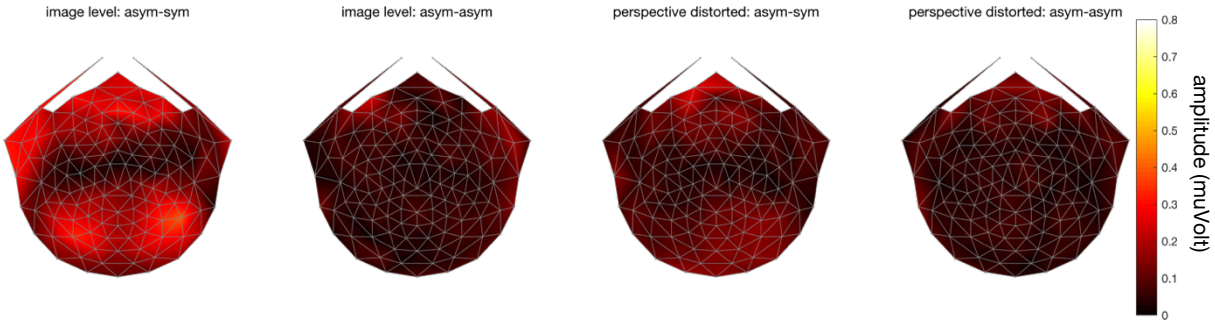

Figure 13 First harmonic topographies, Experiment 2 (2D) (matched 2D group). Whole-scalp topographies based on the coherent average of the first harmonic (1f1) of individual participant amplitudes in Experiment 2 (2D) (matched 2D group). The symmetry response can be observed as the difference between the topographies produced by the test conditions (asymmetric and symmetric) and the control conditions (asymmetric and asymmetric).

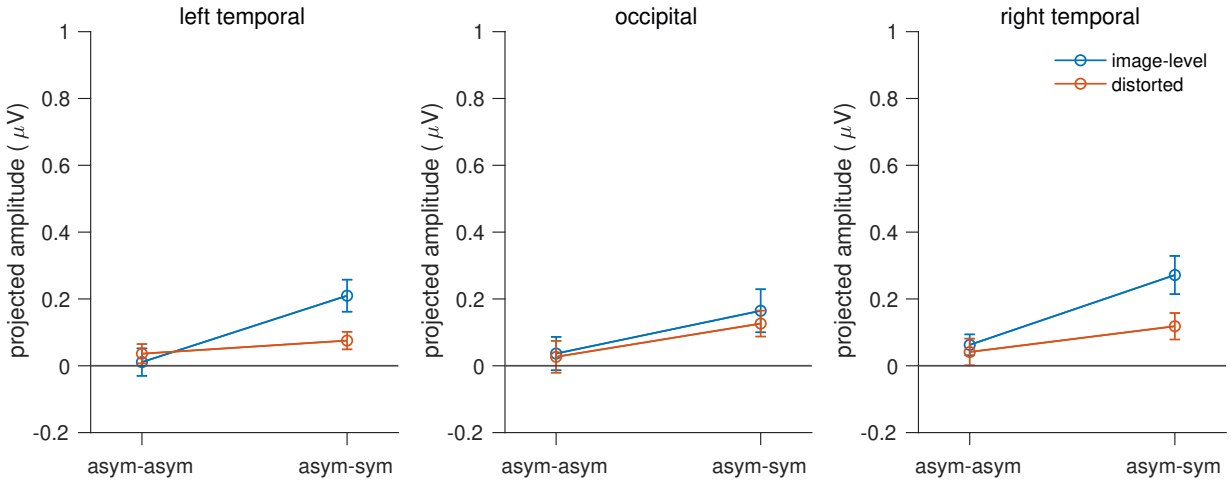

Figure 14 First harmonic ROI analysis, Experiment 2 (2D) (matched 2D group). ROI analysis comparing projected amplitudes in control (asymmetric and asymmetric) and test (asymmetric and symmetric) conditions in the first harmonic (1f1) of the stimulation frequency in Experiment 2 (2D) (matched 2D group). The straight line displayed in this image indicates where zero is.

Next, we present the results of the Hotelling's T^2 test, which allowed us to test, for each electrode separately, whether the test and control conditions elicited distinct responses. The topography in Figure 15 display the significance at each electrode based on the first harmonic in Experiment 1 (3D). The figure shows a comparison of where we see significant responses. Figures 16 and 17 display the electrode-by-electrode Hotelling's T^2 test maps for the 2D ANN and 2D matched groups, respectively. Consistent with the other analyses, we see that effects are generally stronger for image-level symmetry, and that the 2D perspective-distorted stimuli yield very few significant electrodes.

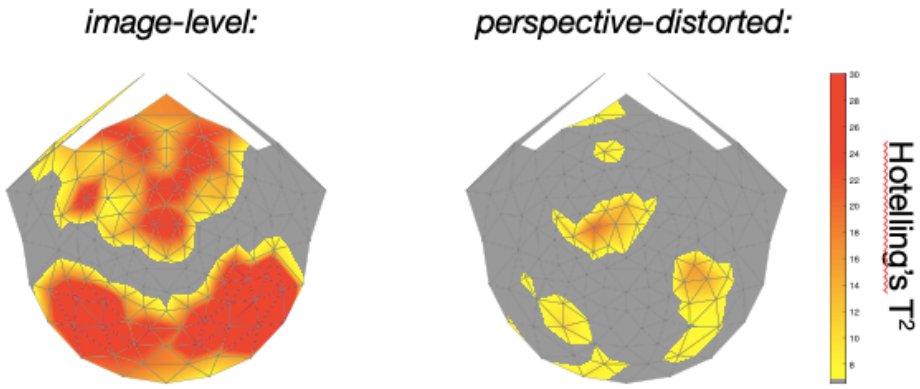

Figure 15 Electrode-by-electrode analysis, Experiment 1 (3D). An electrode-by-electrode Hotelling's T^2 test incorporating both phase and amplitude, comparing test (asymmetric and asymmetric) and control conditions (asymmetric and symmetric) in Experiment 1 (3D). These maps display the significance at each electrode based on the first harmonic (1f1).

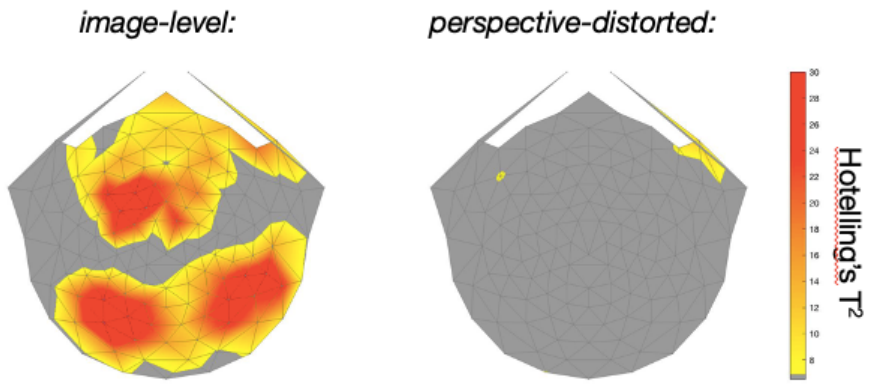

Figure 16 Electrode-by-electrode analysis, Experiment 2 (2D) (ANN 2D group). An electrode-by-electrode Hotelling's T^2 test incorporating both phase and amplitude, comparing test and control conditions (asymmetric and asymmetric vs asymmetric and symmetric) in Experiment 2 (2D) (ANN 2D group). These maps display the significance at each electrode based on the first harmonic (1f1).

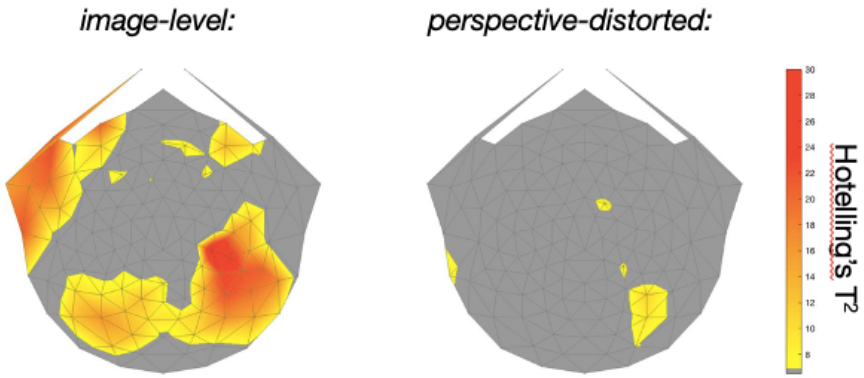

Figure 17 Electrode-by-electrode analysis, Experiment 2 (2D) (matched 2D group). An electrode-by-electrode Hotelling's T^2 test incorporating both phase and amplitude, comparing test and control conditions (asymmetric and asymmetric vs asymmetric and symmetric) in Experiment 2 (2D) (matched 2D group). These maps display the significance at each electrode based on the first harmonic (1f1).

Finally, we present the results of our correlation analysis comparing projected amplitudes (from the test conditions for image-level and perspective-distorted stimuli) and AQ scores in the 3D data set for all ROIs. The results showed that in the right temporal ROI, there were weak correlations for image-level stimuli ($r = -0.11$, $p = 0.57$) and perspective-distorted stimuli ($r = 0.14$, $p = 0.45$) (see Figure 19). In the occipital ROI, there were weak correlations for image-level stimuli ($r = 0.04$, $p = 0.84$) and

perspective-distorted stimuli (r = 0.25, p = 0.20) (see Figure 20). In the left temporal ROI, there were weak correlations for image-level stimuli (r = -0.10, p = 0.61) and perspective-distorted stimuli (r = 0.26, p = 0.18) (see Figure 21). Based on previous work, we would expect people with high AQ scores to be more sensitive to symmetry, so we would predict a positive correlation between AQ scores and response amplitudes. While we did see that for some measurements in some ROIs (see Figures 19 to 20), none of the correlations reached significance (lowest p = 18). Notably, only 2 participants scored above the cut off score of 29. A score above 29 is the proposed cut off, indicating notable traits of autism (Woodbury-Smith et al., 2005).

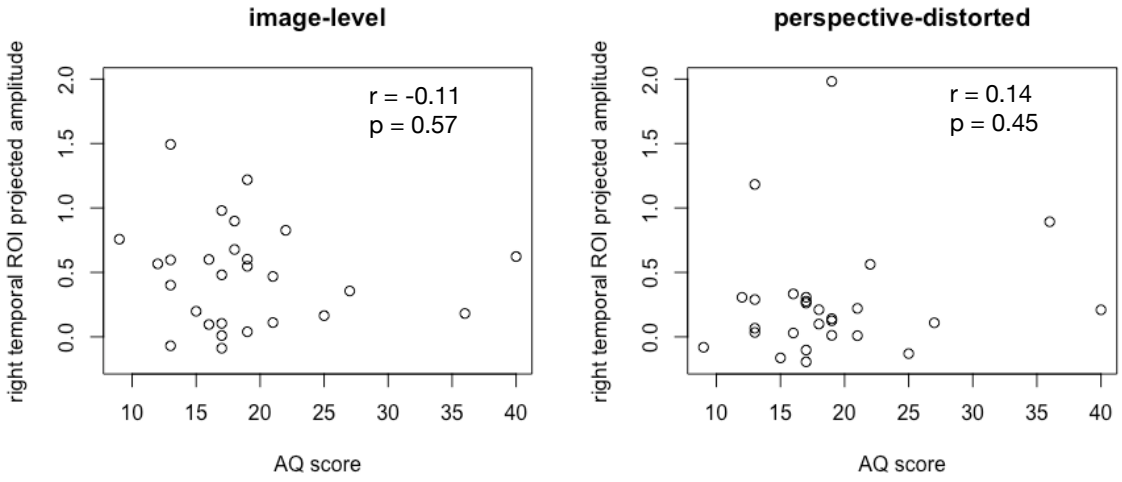

Figure 18 Experiment 1 (3D) AQ score and projected amplitude correlation in the right temporal ROI. Comparison of the difference in responses to image-level and perspective-distorted stimuli in the right temporal ROI.

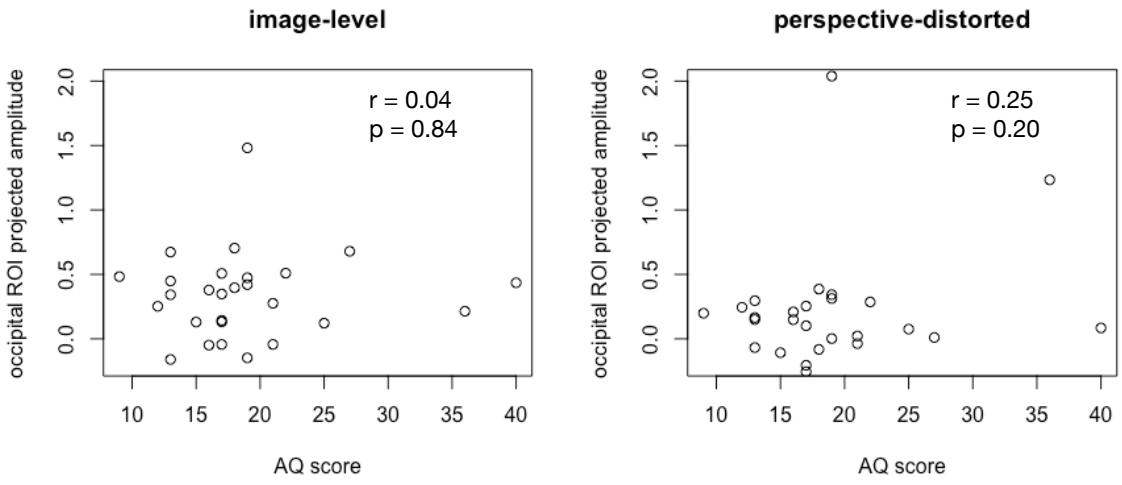

Figure 19 Experiment 1 (3D) AQ score and projected amplitude correlation in the occipital ROI. Comparison of the difference in responses to image-level and perspective-distorted stimuli in the occipital ROI.

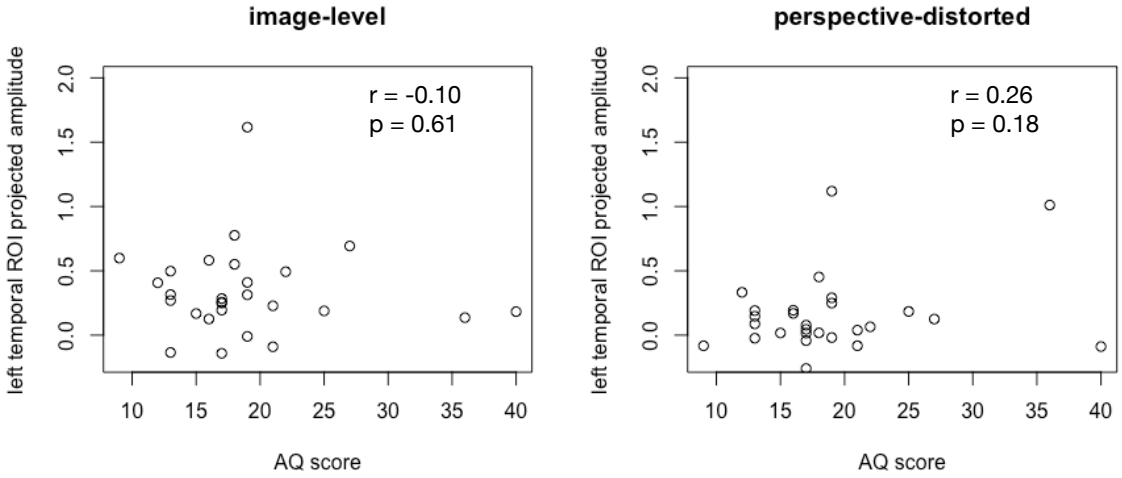

Figure 20 Experiment 1 (3D) AQ score and projected amplitude correlation in the left temporal ROI. Comparison of the difference in responses to image-level and perspective-distorted stimuli in the left temporal ROI.

4. Discussion

4.1 Summary of Experiment 1 (3D) results

We found measurable responses to both image-level and perspective-distorted symmetry. Responses to symmetry were mediated by view, as demonstrated by the significant two-way interaction between symmetry and view factor. In line with our hypothesis, perspective-distorted symmetry was measurable, as demonstrated by the post hoc t-tests. Although there were no interactions with ROI, symmetry responses were generally larger in the right temporal ROI, compared to the left temporal and occipital ROIs, for both image-level and perspective-distorted symmetry.

4.2 Summary of 2D results

In Experiment 2 (2D), we would expect to see an interaction between symmetry and view for both the ANN and matched 2D groups. In the matched 2D group, the presence of this interaction would show that any symmetry effects observed in the 3D perspective-distorted symmetry stimuli was a result of cues to 3D shape, such as depth, since the matched 2D group objects were exact copies of the 3D images, without cues to 3D shape, such as depth and shading. The presence of this interaction in the ANN 2D group would show that there were no confounds in our experimental design, since pairs of images in this group were well matched for low to mid-level differences.

In the ANN 2D group, there were significant main effects of ROI and view factor, and one significant three-way interaction between ROI, symmetry factor and view factor. There was a response to objects with image-level symmetry in the right temporal ROI only, and no response to objects with perspective-distorted symmetry stimuli in any of the ROI's.

While there was a significant main effect of symmetry in the matched 2D group, surprisingly, we found no significant interaction with view, suggesting that a symmetry response could be found for both the image-level and perspective-distorted stimuli. It is important to note, however, that our post-hoc t-tests found no significant differences between our test and control conditions for perspective-distorted symmetry, for any of the ROIs. For image-level, significant differences were found for all 3 ROIs. The absence of an interaction may be a result of the images not being well matched for low

to mid-level visual features, since image pairs in this group were never correlated to ensure that the ANN activations elicited by the two images had a correlation of 0.45±0.01.

The main purpose of the 2D matched group in Experiment 2 was to compare the image-level responses in this group to the image-level responses in Experiment 1 (3D), since they are the same images without cues to 3D shape. This comparison allowed us to observe that symmetry responses are stronger for richer stimuli compared to 2D stimuli. On the other hand, the 2D ANN group in Experiment 2 has an equal chance of revealing an effect as Experiment 1 (3D), therefore testing whether there are any confounds in the experimental design. The results of the statistical analyses do suggest that each of these tests were successful.

4.3 Image-level response differences between Experiment 1 (3D) and Experiment 2 (2D)

The symmetry response, operationalized as the difference between the test and control conditions, was larger for image-level responses in the 3D condition across all three ROI's compared to in the 2D conditions. In both 3D and 2D conditions, the right temporal ROI showed the greatest significance, followed by the left temporal ROI. The occipital ROI showed the lowest levels of significance in both the 3D and 2D conditions. One possible explanation for why there was a stronger response for 3D image-level symmetry is that 3D objects are more capable of driving the mechanism response for symmetry processing. However, it is important to consider that there are more details and variety in the 3D image, at the pixel level, compared to the 2D image. These additional details may modulate symmetry processing and elicit a greater response.

4.4 Comparison of image-level and perspective-distorted symmetry

Furthermore, in Experiment 1 (3D), the scalp topography and response amplitudes for perspective-distorted symmetry were somewhat different from those generated by image-level symmetry. Perspective-distorted symmetry elicited SSVEPs comparable to those elicited by image-level symmetry. The results of the post hoc t-tests suggest that these responses may be more right lateralized (associated with the

right temporal cortex ROI) and in more anterior scalp regions. Responses in these areas may be driven by activity in higher level visual cortex, such as in the temporal cortex.

Furthermore, there were significant differences between the test and control conditions for both perspective-distorted and image-level symmetric stimuli across all ROIs, however, the magnitude of these differences varied between the two types of stimuli, with the image-level stimuli exhibiting larger effect sizes compared to perspective-distorted stimuli.

4.5 Electrode-by-electrode Hotelling's T^2 test results

The electrode-by-electrode Hotelling's T^2 tests were done to have an electrode-by-electrode comparison of where responses were elicited. For Experiment 1 (3D) (see Figure 15), results were consistent with the ROI analysis. Image-level stimuli elicited responses associated with all 3 ROIs, while perspective-distorted stimuli appeared to mostly elicit significant symmetry responses at more posterior electrode locations on the right side of the scalp.

4.6 Perspective-distorted symmetry

Previous research shows that responses to perspective-distorted symmetry are weaker than to image-plane symmetry (Keefe et al., 2018, p. 20), and only measurable when participants are engaged in symmetry-related task (Makin et al., 2015). Furthermore, it has been shown that that symmetry processing occurs automatically (Bertamini et al., 2018; Treder, 2010), but that attention modulates symmetry processing (Keefe et al., 2018; Rampone et al., 2014).

In the current study, symmetry responses to distorted symmetry were observed under passive viewing conditions, with no task. These results support the theory that symmetry processing occurs automatically, and goes against the theory that perspective-distorted symmetry elicits symmetry responses only with task involvement. However, it is important to note that while there was no task involvement, observers could have voluntarily paid attention to the symmetry in the images. Such attention

could have influenced the symmetry response observed. This limitation is further discussed below.

Furthermore, these results may be due to the stimuli used, which differs from previous studies. In the current study, we compared brain responses to procedurally generated novel, naturalistic, 3D objects. These stimuli closely approximate objects observed during natural viewing, while maintaining novelty, which ensures that participants do not place meaning on the images observed. This means that responses occur due to symmetry processing, as opposed to identification with familiar objects. The 3D objects were rich and detailed, and elicited responses stronger than those of their 2D counterparts.

Furthermore, the SSVEP technique has not previously been used to investigate perspective-distorted symmetry. It may be the case that this paradigm is more sensitive to perspective-distorted symmetry processing than others.

4.7 Brain areas involved with symmetry processing

It is important to note that there was a symmetry response for perspective-distorted symmetry, although it was slightly different than the response observed from image-level symmetry. Image-level symmetry elicited more broad responses across all three ROIs (occipital as well as left and right temporal cortices). Perspective-distorted symmetry elicited significant, although, less pronounced responses in the left temporal cortex and the occipital cortex, with a greater right lateralization effect. This finding is in line with previous studies which demonstrate that the right LOC is involved with shape detection based on contour integration. It may be the case that brain regions that are highly sensitive to symmetry, such as the LOC, can still be activated when symmetrical objects do not reflect symmetry on the retina (Bona et al., 2014). The results from the current study are in line with previous studies which demonstrate that there is a right lateralization effect during symmetry processing (Bertamini & Makin, 2014; Bona et al., 2014).

4.8 Right-lateralization in symmetry processing

Studies of visual symmetry perception show that brain responses to symmetry occur in extra-striate visual areas (V3, V4, intraparietal sulci, ventral occipital area VO1), and the LOC (Keefe et al., 2018; Kohler et al., 2016; Sasaki et al., 2005) and not in early visual areas V1 or V2 (Kohler et al., 2016; Sasaki et al., 2005). Symmetry responses in these areas have been found to show evidence of right lateralization. In the current study, there were no interactions with ROI, which would have shown that responses vary significantly between our three ROIs (left and right temporal, and occipital cortices). However, in the post hoc t-tests, we did see larger effects for the right temporal ROI compared to the occipital and left temporal. While these results do not definitively suggest that there was a right lateralization effect, it is worth noting previous evidence of a right lateralization effect in symmetry processing, as this pattern has been observed often, and can inform which brain regions may have been activated in the current study.

Symmetry detection occurs more efficiently when stimuli are presented only to the left hemifield (versus only the right hemifield) (Verma et al., 2013). Because left hemifield stimuli are processed in the right visual cortex, this is evidence of a right laterality effect. Furthermore, Makin et al. (2014) found a right lateralization of an event related desynchronization (ERD) in the occipital alpha rhythm only when participants were engaged with a symmetry related task (not when engaged in a non-symmetry related task). It is important to note that in this particular study, the right lateralization was specifically associated with a symmetry-related task, not simply processing of symmetry. Notably, the fMRI literature provides limited support for right lateralization of symmetry responses. A recent study investigating responses to symmetries in textures found no evidence of lateralization (Kohler et al., 2016, figure 7), and other prominent fMRI studies did not analyze the two hemispheres separately (Keefe et al., 2018; Sasaki et al., 2005).

Transcranial magnetic stimulation (TMS) studies have also offered evidence for lateralization of symmetry processing. An area in the inferior occipital gyrus called the occipital face area (OFA) is known to be implicated in face perception (Solomon-Harris et al., 2013; Zhao et al., 2014), as well as the perception of other visual stimuli such as 2D images with vertical mirror symmetry (Silvanto et al., 2010). Bona et al. (2015), used

fMRI guided TMS to show that the right LOC and the right OFA, but not left OFA are causally implicated in symmetry detection of dot patterns. Right LOC but not right OFA were causally involved in detection of symmetric/asymmetric Gabor patches, showing that right OFA is sensitive to symmetry but not to certain figure-ground cues such as those found in Gabor patches. When testing the difference in processing or horizontal and vertical symmetry, Cattaneo et al. (2017) found that vertical symmetry detection is compromised when TMS is applied over right LOC and right OFA. Additionally, Chen et al. (2007) found that right OFA may be specialized for processing symmetry in faces. The stimuli used in this study were naturalistic and had vertical symmetry axis', with features that could be representative of those found in faces. Additionally, following EEG recording, some participants spontaneously mentioned that the objects looked like faces and animals. It is possible the stimuli used in this study, while abstract, were still able to activate brain regions associated with facial symmetry processing.

Overall, findings suggest that only right OFA (not left OFA) is involved in symmetry detection (Bona et al., 2015; Cattaneo et al., 2017). And while both right and left LOC play a role, right LOC is more sensitive to symmetry than left LOC (Bona et al., 2014; Cattaneo et al., 2017). While OFA is mainly involved with face perception (Solomon-Harris et al., 2013; Zhao et al., 2014), the results from Bona et al., (2015), Chen et al., (2007), and Silvanto et al., (2010) suggest that it is also involved in symmetry perception, specifically vertical symmetry (Cattaneo et al., 2017) because vertical symmetry is a crucial cue to face perception. Therefore, it may be the case that OFA is involved in non-face stimuli perception only to the extent that the given stimuli are also relevant for face perception.

In summary, the neuroimaging literature on symmetry suggests that the scalp EEG responses measured in our study are likely driven by regions known to show prominent responses to symmetry, such as V4, VO1 and LOC. In addition, OFA may also play a role in driving the responses, either because OFA plays a general role in symmetry processing, or because our naturalistic 3D stimuli with vertical symmetry axes have some similarities with faces.

4.9 AQ results

In the current study, there was no relationship between AQ results and projected amplitudes in response to perspective-distorted and image-plane symmetry. Another study has demonstrated a relationship between symmetry processing and ASD (Perreault et al., 2011), wherein participants diagnosed with ASD were better able to detect vertical symmetry in stimuli. This effect was presumably due to differences in global processing between those with and without ASD. However, in the current study there was no relationship between AQ scores and projected amplitudes in symmetry processing. This discrepancy may be due to differences in stimuli and samples. While Perreault et al., (2011) used dot pattern stimuli, the current study used images of naturalistic 3D objects. Perrault et al., (2011) used a behavioural task that measured thresholds for symmetry detection within noise. It may be the case that this measure is more sensitive than the EEG measure used in the current study. Furthermore, Perrault et al. (2011) recruited ASD participants and compared them to a control group, while in the current study, a correlation analysis was used, and ASD participants were not recruited. Furthermore, only two of our participants scored above the AQ cut off score of 29.

4. 10 Limitations

Several limitations should be addressed in future work. The current study recruited university students between the ages of 18 and 54 years, and conclusions can only be made based on this population. Restricting the ages of participants to a smaller range may provide more specific results as to differences in symmetry perception between older and younger people.

Furthermore, symmetrical objects were rotated to the left, relative to the camera. Including other forms of perspective distortion may provide insight as to whether orientation of rotation changes the brain responses observed. For example, rotating images to the right, upward or downward may elicit different responses.

Additionally, adding surface texture to the objects may add additional details that make symmetry perception more efficient, since it is not possible to eliminate the possibility of there only being a greater symmetry response from our 3D images due to richness of the image (not due to cues to 3D shape). The uniformity of the objects may

also be manipulated, since the objects in the current study were very uniformed, and always made of the same spheres. It may have been the case that the uniformity of the objects created more or less of a response.

Additionally, an fMRI study would be helpful to identify the specific regions involved in processing our novel stimuli. An fMRI guided TMS study in which TMS is used to disrupt LOC and OFA regions (or other locations sensitive to symmetry) in the brain would help to identify regions causally involved in perceiving perspective-distorted symmetry. This is helpful, as EEG studies do not provide strong insight as to which brain areas are being recruited.

Most notably, future work should investigate the role of task (both symmetry specific and non-symmetry related tasks) to determine how and when task involvement and attention modulates brain responses to symmetry (Kay et al., 2023). As previously mentioned, one limitation of this study was the possibility of participants voluntarily paying attention to the symmetric images, even without task involvement. Therefore, we cannot definitively say that the stimuli elicited a symmetry response without the participants paying attention to the symmetry. Future studies should manipulate attention by including tasks that direct attention to and away from the symmetric stimuli, and observing whether there is a symmetry response when a task requires participants to direct their attention away from the stimuli.

Lastly, future work may involve choosing to recruit specifically for participants with ASD in order to compare a group of participants with ASD and a group without ASD. This comparison could possibly uncover a difference in symmetry responses between the two groups when using the SSVEP methodology.

5. Conclusion

We found that perspective-distorted symmetry in naturalistic, novel 3D objects generated a symmetry response in the brain using an SSVEP paradigm. Whole scalp topographies and response amplitudes differed between image-level and perspective distorted symmetry, with image-level symmetry produces stronger responses in more posterior regions. Lastly, we did not find a relationship between AQ scores and perspective-distorted and image-level symmetry.

These results suggest that symmetry processing can occur in the absence of a symmetry-related task, even for perspective-distorted symmetry. These experiments provide insight into the process by which, and the possible brain locations in which 3D representations of objects may occurs.

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Appendix A

Autism Quotient

How to fill out the questionnaire:

Below is a list of statements. Please read each statement very carefully and rate how strongly you agree or disagree with it.

1 I prefer to do things with others rather than on my own.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

2 I prefer to do things the same way over and over again.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

3 If I try to imagine something, I find it very easy to create a picture in my mind.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

4 I frequently get so strongly absorbed in one thing that I lose sight of other things.

- Definitely agree.
- Slightly agree.
- Slightly disagree.

- Definitely disagree.

5 I often notice small sounds when others do not.

5 I usually notice car number plates or similar strings of information.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

6 Other people frequently tell me that what I've said is impolite, even though I think it is polite.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

7 When I'm reading a story, I can easily imagine what the characters might look like.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

8 I am fascinated by dates.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

9 In a social group, I can easily keep track of several different people's conversations.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

10 I find social situations easy.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

11 I tend to notice details that others do not.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

12 I would rather go to a library than a party.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

13 I find making up stories easy.

- Definitely agree.
- Slightly agree.

- Slightly disagree.
- Definitely disagree.

14 I find myself drawn more strongly to people than to things.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

15 I tend to have very strong interests which I get upset about if I can't pursue.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

16 I enjoy social chit-chat.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

17 When I talk, it isn't always easy for others to get a word in edgeways.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

18 I am fascinated by numbers.

- Definitely agree.

- Slightly agree.
- Slightly disagree.
- Definitely disagree.

19 When I'm reading a story, I find it difficult to work out the characters' intentions.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

20 I don't particularly enjoy reading fiction.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

21 I find it hard to make new friends.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

22 I notice patterns in things all the time.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

23 I would rather go to the theatre than a museum.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

24 It does not upset me if my daily routine is disturbed.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

25 I frequently find that I don't know how to keep a conversation going.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

26 I find it easy to "read between the lines" when someone is talking to me.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

27 I usually concentrate more on the whole picture, rather than the small details.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

28 I am not very good at remembering phone numbers.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

29 I don't usually notice small changes in a situation, or a person's appearance.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

30 I know how to tell if someone listening to me is getting bored.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

31 I find it easy to do more than one thing at once.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

32 When I talk on the phone, I'm not sure when it's my turn to speak.

- Definitely agree.
- Slightly agree.
- Slightly disagree.

- Definitely disagree.

33 I enjoy doing things spontaneously.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

34 I am often the last to understand the point of a joke.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

35 I find it easy to work out what someone is thinking or feeling just by looking at their face.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

36 If there is an interruption, I can switch back to what I was doing very quickly.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

37 I am good at social chit-chat.

- Definitely agree.

- Slightly agree.
- Slightly disagree.
- Definitely disagree.

38 People often tell me that I keep going on and on about the same thing.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

39 When I was young, I used to enjoy playing games involving pretending with other children.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

41 I like to collect information about categories of things (e.g. types of car, types of bird, types of train, types of plant, etc.).

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

42 I find it difficult to imagine what it would be like to be someone else.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

43 I like to plan any activities I participate in carefully.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

44 I enjoy social occasions.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

45 I find it difficult to work out people's intentions.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

46 New situations make me anxious.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

47 I enjoy meeting new people.

- Definitely agree.
- Slightly agree.
- Slightly disagree.

- Definitely disagree.

48 I am a good diplomat.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

49 I am not very good at remembering people's date of birth.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.

50 I find it very easy to play games with children that involve pretending.

- Definitely agree.
- Slightly agree.
- Slightly disagree.
- Definitely disagree.