Symmetry versus repetition in cyclopean vision: A microgenetic analysis

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Abstract

In four experiments, participants had to detect symmetries or repetitions distributed over two depth planes, under presentation times of 200–1000 ms. Structurally corresponding elements were placed in different planes (Experiments 1a and 1b) or in the same plane (Experiments 2a and 2b). Results suggest (a) an ongoing interaction between regularity cues and depth cues, and (b) that efficient detection of symmetry but not of repetition depends on structural correspondences within depth planes. The latter confirms the idea that, to perceptual organization, symmetry is a cue for the presence of one object, whereas repetition is a cue for the presence of multiple objects.
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1. Introduction

To human observers, there are substantial perceptual differences between kinds of visual regularity. Most comparative studies are dedicated to contrasting the two most prominent cases, namely mirror symmetry (henceforth symmetry) and twofold repetition (henceforth repetition). These studies show consistently that symmetry has a higher goodness than repetition. For instance, symmetry is more salient and more noise-resistant than repetition; furthermore, in terms of the number of stimulus elements covered, symmetry detection seems to propagate exponentially by way of parallel processing, whereas repetition detection seems to propagate linearly by way of serial processing (Baylis & Driver, 1994; Bruce & Morgan, 1975; Corbalis & Roldan, 1974; Csathó, van der Vloed, & van der Helm, 2003; Fitts, Weinstein, Rappaport, Anderson, & Leonard, 1956; Julesz, 1971; Mach, 1886/1959; van der Helm & Leeuwenberg, 1996, 1999, 2004; Zimmer, 1984).

In fact, symmetry and repetition seem to have opposite effects on the perceptual formation of objects. Symmetry seems to integrate pattern halves into perceived wholes, while repetition rather seems to signal the presence of two distinct objects (for a tentative explanation, see van der Helm & Leeuwenberg, 1996; for accounts of the general problem of perceptual object formation, see e.g., Feldman, 1999, van der Helm, van Lier, & Wagemans, 2003). There are some empirical indications for this dichotomy. For instance, Baylis and Driver (1995, 2001) had participants discriminate symmetric from asymmetric and repetitive from non-repetitive vertical curves which were part of the contour of either the same object or different objects. They found that symmetric curves are detected more easily than repeated curves when they belong to the same object, whereas repeated curves are detected more easily than symmetric curves when they belong to different objects. However, it is questionable to speak of symmetry in the two-object stimuli and of repetition in the one-object stimuli because, in these cases, the contour polarity of the curves goes against the regularity (see Fig. 1). Hence, in these cases, we would rather speak of anti-symmetry and anti-repetition. A similar argument applies to Bertamini, Friedenberg, and Kubovy (1997), who compared symmetry to what we would call anti-repetition.

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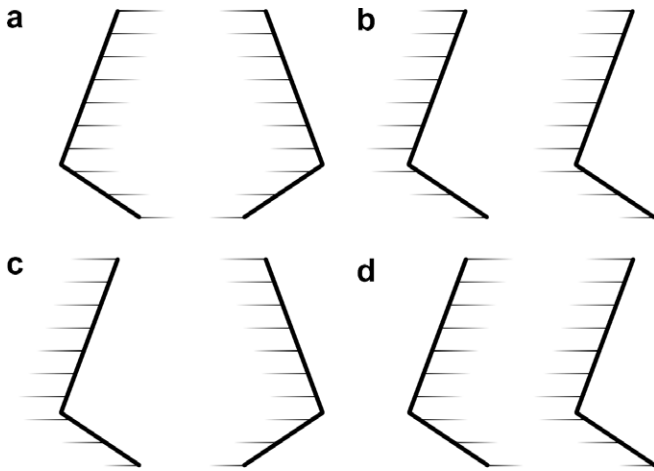 *URL:* http://www.nici.ru.nl/~peterh (P.A. van der Helm).

Fig. 1. Schematic overview of stimuli used by Baylis and Driver (1995, 2001). The vertical contours belong to surfaces with interiors indicated by horizontal stripes. In the top row, contour polarity (i.e., concavity/convexity) goes along with the regularity between the contours. We therefore call (a) a true symmetry and (b) a true repetition. In the bottom row, contour polarity goes against the regularity between the contours. We therefore call (c) an anti-symmetry and (d) an anti-repetition.

Stronger evidence stems from an experiment conducted by Corbalis and Roldan (1974). They had participants discriminate between symmetric and repetitive patterns in which the pattern halves were either adjacent or separated by a fixed distance. They found that symmetry is more salient than repetition when there is no spatial separation between the pattern halves but not when there is a spatial separation between the pattern halves. Apparently, manipulation of the distance between pattern halves within the projection plane has different, if not opposite, effects on symmetry as compared to repetition.

In this study, we put visual regularity in direct competition with another significant determinant of perceptual organization, namely, stereoscopic depth. When relative disparity exceeds a certain threshold (Yakushijin & Ishiguchi, 1999), it provides metrical information about distances and locations in depth (cf. Burge, Peterson, & Palmer, 2005). As a consequence, depth influences the grouping of parts into objects, because spatially contiguous parts tend to be perceived as belonging to the same object. However, the processing of relative disparity takes time to become effective (Ritter, 1980), and we wondered whether and, if so, how this affects regularity perception. That is, we think that both regularity perception and stereopsis are ongoing processes, and in this study, we investigate the interaction between these two ongoing processes. This issue may be introduced as follows.

Hitherto, comparative studies on symmetry and repetition in depth are rare. It is true that van der Vloed, Csathó, and van der Helm (2005) investigated the effect of linear perspective on the discriminability of symmetry and repetition, and that Farell (2005) probed the detectability of visual regularities defined by disparity values, but to our knowledge, there are no comparative studies on stereo-

scopic manipulations of symmetry and repetition. Only for symmetry alone, several studies did examine detectability in stereoscopic space; this is discussed next.

The first explorations into symmetry and binocular viewing were conducted by Julesz (1960, 1966). He demonstrated that a binocular symmetry percept can arise even in the absence of monocular symmetry and that monocular symmetry can be destroyed by appropriate binocular cues. These findings led him to conclude that symmetry detection is preceded or dominated by stereo vision. This is in line with Ishiguchi and Yakushijin (1999) who had participants discriminate between patterns consisting of two or three depth planes with varying interplanar distances. They found that the disparity threshold to distinguish between depth planes is not affected by the structure (symmetry or random) of the patterns in each plane. Furthermore, Yakushijin and Ishiguchi (1999) found that, when symmetry and noise are placed in different depth planes, the detectability of symmetry in the symmetry plane is unaffected by the noise plane, provided that the relative disparity between the planes is sufficiently large. Finally, Bertone and Faubert (2002) found that the detectability of symmetry deteriorates with increasing disparity when pattern halves are put into different depth planes. However, even for large disparities, symmetry detection remained feasible. Apparently, to a certain extent, depth separation induced by binocular disparity can be overcome.

At first glance, these results seem to be contradicted by Locher and Smets (1992), who proposed that symmetry is detected before the integration of figural and disparity cues. However, these two points of view do not have to exclude each other. In contrast to classical views which state that grouping is preattentive and operates on the retinal image, recent research suggests that perceptual grouping can be influenced significantly by factors such as lightness constancy, amodal completion and binocular disparity (Palmer, 2002; Palmer, Brooks, & Nelson, 2003). Furthermore, whether or not grouping is preceded by these factors seems to depend strongly on exposure time: For short exposure times, subjects seem to base their response on retinal properties while the aforementioned factors come into play for long exposure times (Schulz & Sanocki, 2003).

These effects may partly be due to the fact that different features of the visual input are processed in functionally more or less specialized streams (Ungerleider & Mishkin, 1982; for recent evidence, see Borowsky, Loehr, Kraushaar, Kingstone, & Sarty, 2005). While shape processing seems largely confined to the ventral stream, stereoprocessing seems to occur in both dorsal and ventral areas (Chandrasekaran, Canon, Dahmen, Kourtzi, & Welchman, 2007; Neri, 2004). This suggests that there is a certain degree of neural dissociation but also interaction between shape processing and stereoprocessing. Consequently, the detection of visual regularities in a stereoscopic context (with visual regularity co-defining a Gestalt and disparities encoding its location) is probably a dynamic process in

which different forces of perceptual organization dominate at different points in time.

A comprehensive approach to the detection of visual regularities in depth thus requires a microgenetic analysis of the interaction between the ongoing processes of regularity perception and stereopsis (to be clear, the concept of microgenesis refers to the development on a brief present-time scale of, in this case, a percept; see e.g., Sekuler & Palmer, 1992). To this end, in our experiments, both temporal and spatial aspects of the stimulus material were manipulated. With respect to the temporal domain, we varied presentation time from 200 to 1000 ms to probe the detection mechanism at different stages of visual processing. With respect to the spatial domain, we subjected regularities to various kinds of stereoscopic manipulations to test the resistance of the detection mechanism to spatial displacements of pattern elements. First, for symmetry in Experiment 1a and for repetition in Experiment 1b, we investigated the effects of assigning non-corresponding disparity values to structurally corresponding elements (yielding one regularity spread out across two depth planes). Second, in Experiments 2a and 2b, we compared this to the effects of assigning corresponding disparity values to structurally corresponding elements (yielding two depth planes featuring one regularity each).

2. Experiments 1a and 1b

2.1. Methods

2.1.1. Participants

In each of the experiments, 22 subjects participated (no overlap between the two groups). The participants were either undergraduate students or volunteers with normal or corrected-to-normal vision and good stereopsis. To assess whether participants were able to perceive stereoscopic depth, we had them look at stereoscopic dot displays while wearing shutter glasses and asked them to describe their percept. In return for their participation, they received either course credits or money.

2.1.2. Apparatus

The experiments were run on a standard PC with a 19″ monitor with a 140 Hz refresh rate and a resolution of 1024×768 pixels. The screen was viewed through a 16×16 cm hole in a black piece of cardboard; this was done because pilot experiments suggested that viewing the stimuli through such a hole eases stereopsis when the cardboard has a few centimeters offset from the screen. During the experiment, participants wore wireless Crystal-Eyes 3 shutter glasses. An infrared emitter synchronized the shutter glasses with the refresh rate of the screen. Responses were recorded via a button box.

2.1.3. Stimuli

Stimuli consisted of 60 dark grey discs with a diameter of 0.42° of visual angle on a light grey background. The

luminance of the discs amounted to 0.63 cd/m^2 and the luminance of the background was 28.49 cd/m^2. The whole pattern had a size of $12° \times 12°$ of visual angle. Stereoscopically, stimuli comprised three depth planes, two frontoparallel target planes constituting the regularity or its random counterpart (20 discs in total, 10 discs per target plane), and a frontoparallel noise plane in the background (40 discs). The position of the first target plane in stereoscopic space coincided with the computer screen. The relative disparity to the second target plane and the noise plane amounted to +26.4′ and +49′ (i.e., target plane 2 was located behind target plane 1 and the noise plane was the hindmost plane; see Fig. 2a). The noise plane was included not only to control task difficulty but also to stimulate an effective usage of binocular cues. That is, participants can perform the task more efficiently when using binocular cues to separate the noise plane from the target planes (see also Yakushijin & Ishiguchi, 1999).

The target planes were constructed by starting from planar regular or random patterns. In Experiment 1a, the symmetry patterns were generated by randomly placing 10 discs in one half of a pattern and then reflecting this pattern half about a vertical axis. For the repetition patterns in Experiment 1b, this pattern half was copied without reflection. To generate random patterns, discs in the left-hand and right-hand halves were distributed randomly. Both Experiments 1a and 1b contained three stimulus conditions, namely, *LR* (left–right), *Opp* (opposite), and *Base* (baseline). These conditions differed in the way the discs were assigned disparity values to place them in one of the two target planes, as follows.

In the *LR* condition, the discs were assigned disparity values such that the pattern halves were placed in different planes. In the *Opp* condition, the symmetry or repetition pairs were divided randomly into two subsets of equal size. In one subset, the left-hand disc of each pair was placed in the first target plane and the right-hand disc in the second target plane; in the second subset, the disparities were reversed. Fig. 2b schematically depicts the *LR* and *Opp* stimuli used in the experiments. The frontoparallel projection of the two target planes always yielded a perfect planar regularity, irrespective of the manipulation performed. In both experiments, we also included a baseline condition *Base* with only one target plane, that is, all discs were assigned the same disparity, thus confining the regularity to either the first or the second target plane. To the random counterparts of these three conditions, the same manipulations were performed. The assignment of disparity values was counterbalanced within each condition.

2.1.4. Procedures

Participants were seated at 65 cm from the computer screen. Participants in Experiment 1a performed a symmetry present/absent task. In each trial, either a symmetric or a random stimulus was presented and participants had to press a button with their dominant hand when they saw symmetry and another button with their non-dominant
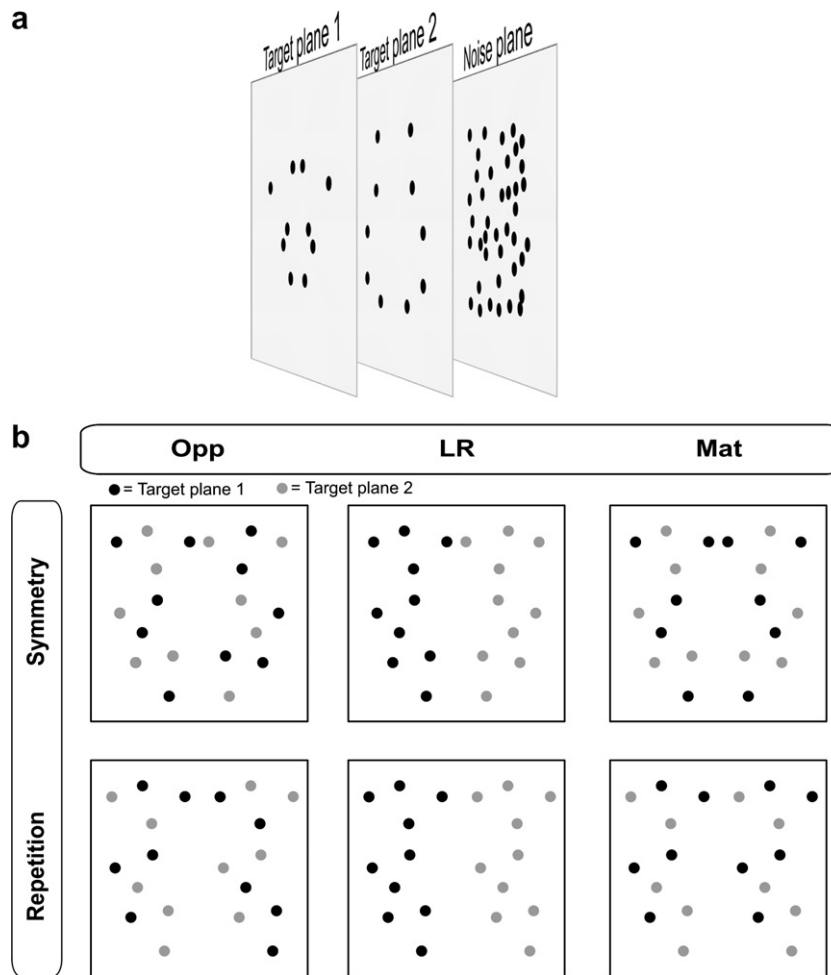
Fig. 2. Overview of the stimuli used in our experiments. (a) Schematic side view of the depth planes. From left to right: target plane 1, target plane 2, and noise plane. From the subject's perspective, target plane 1 was the foremost frontoparallel plane. In this example, the arrangement of discs corresponds to the *Mat* condition for symmetry. (b) Sketch of the pattern types *Opp* (opposite), *LR* (left–right), and *Mat* (matched) for symmetry (first row) and repetition (second row). Just for illustration purposes, the noise plane is omitted, and the discs are coloured light and dark to indicate on which target plane they are located. The additional *Base* condition simply featured a regularity confined to a single plane and is not displayed here.

hand when they did not. Participants in Experiment 1b performed a repetition present/absent task and had to indicate their choice analogously.

A series of 60 practice trials preceded the experimental phase. During practice, stimulus presentation ended only when participants responded. This was necessary, because many participants initially needed a few seconds to get used to the unusual sensation of stereoscopic depth on a computer screen. During the practice phase, visual feedback was given immediately after the response. Immediately after the practice phase, the experimental phase commenced. It was split into five blocks featuring the presentation times 200, 400, 600, 800, and 1000 ms, respectively. The order of presentation times was randomized across participants.

At the beginning of each trial, a fixation cross was presented for 500 ms. To minimize a fixation bias towards one of the target planes, the fixation cross was presented stereoscopically in between the two target planes. Subsequently, the stimulus appeared on the screen. Following the offset of the stimulus, participants were given three seconds to respond. After the response and an inter-trial interval of 100 ms, the next trial commenced automatically. Each time after 120 trials, a break was given and the percentage of correct responses during the last block was displayed. In total, each experiment comprised 5 (presentation times) × 3 (pattern types: *LR, Opp,* and *Base*) × 2 (regular and random) × 20 (measurements) = 600 trials.

2.2. Results

For each experiment separately, and based on hits and correct rejections, d' was calculated for every combination of presentation time (200, 400, 600, 800, and 1000 ms) and pattern type (*Base, LR,* and *Opp*). Compared to the baseline, performance on the other pattern types was significantly lower. For symmetry, repeated measures ANOVAs yielded $F(1, 21) = 58.596$, $p < .001$, and $F(1, 21) = 98.838$, $p < .001$, for *LR* and *Opp*, respectively. For repetition, the corresponding values were $F(1, 21) = 9.237$, $p < .01$, and $F(1, 21) = 86.448$, $p < .001$. However, d' was merely an intermediate step in the specification of a more interest-

ing dependent variable which may be introduced as follows.

By definition, prolonged viewing eases the task and thus enhances d', irrespective of the presence of binocular depth cues. Furthermore, perceptual dissociation of the target and noise planes, which is increasingly feasible with increasing presentation time, gives an additional boost to performance. Indeed, we found that d' increases with presentation time in all conditions, but because of these factors, this does not allow for a straightforward comparison of the pattern types across presentation times. To eliminate these factors from our measurements, we calculated *relative* performance, that is, the performance on *LR* and *Opp* relative to the baseline *Base*. We defined relative detectability $\Delta d'$ by

$$\Delta d'_x = d'_x - d'_{Base}$$

where d'_x corresponds to d' obtained for a pattern type $x \in \{LR, Opp\}$, while d'_{Base} corresponds to d' obtained for the baseline condition. In other words, $\Delta d'$ for the *LR* condition was derived by subtracting d' in the *Base* condition from d' in the *LR* condition. Correspondingly, $\Delta d'$ for the *Opp* condition was derived by subtracting d' in the *Base* condition from d' obtained in the *Opp* condition. This subtraction eliminates the facilitating effects of longer presentation times and of the perceptual dissociation of the target and noise planes, so that any effect found for $\Delta d'$ can be attributed to the kind of manipulation applied to the regularities. A set of repeated measures ANOVAs was performed on the obtained $\Delta d'$ (note that a main effect on $\Delta d'$ for *LR* or *Opp* is statistically equivalent to an interaction in terms of d' between the baseline and *LR* or *Opp*).

2.2.1. Effects of pattern type

For symmetry, participants performed significantly better in the *LR* condition as compared to the *Opp* condition, with $F(1, 21) = 25.088$, $p < .01$ (see Fig. 3). This difference was not significant at a presentation time of 200 ms ($p = .342$), but was significant at 400 ms, $t(21) = 2.104$, $p < .05$, and later. For repetition, the same pattern was found, that is, $LR > Opp$ with $F(1, 21) = 55.512$, $p < .01$ (see Fig. 4); this time, the difference between *LR* and *Opp* is already evident at a presentation time of 200 ms, $t(21) = 2.883$, $p < .01$.

2.2.2. Time effects

We also investigated whether there were effects of presentation time in each of the conditions. For *Opp*, there was a negative time effect on both symmetry and repetition, with $F(4, 18) = 4.150$, $p < .05$, and $F(4, 18) = 3.025$, $p < .05$, respectively. For *LR*, we found a negative effect of time on symmetry, with $F(4, 18) = 3.234$, $p < .05$, but not on repetition ($p = .588$). The time effect on symmetry in the *LR* condition was solely due to a performance drop at 400 ms. That is, two-sided *t*-tests revealed that relative performance at 400 ms was significantly worse than at the immediately preceding (200 ms) and following (600 ms) levels of presentation time, with $t(21) = 3.393$, $p < .01$, and
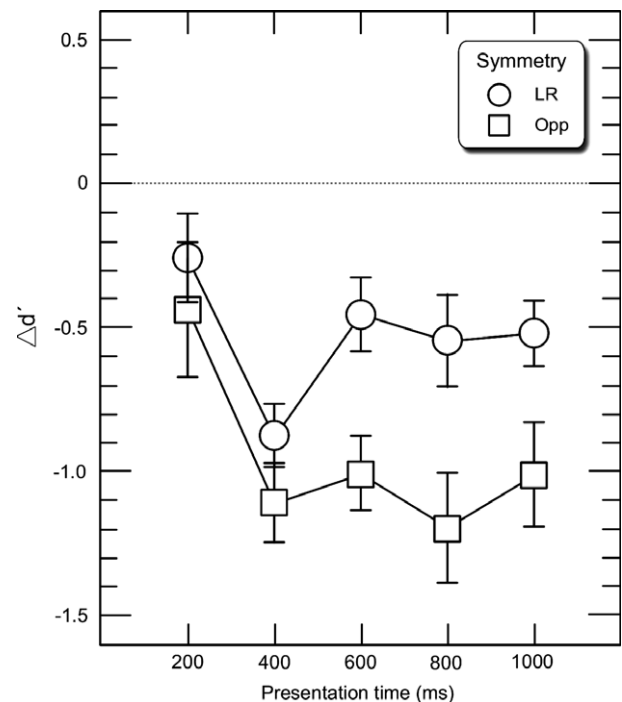

Fig. 3. Results of Experiment 1a: $\Delta d'$ on symmetry as a function of presentation time. The *LR* curve (○) shows a performance dip at 400 ms. The *Opp* curve (□) also drops at 400 ms and then levels off. The dips suggest the *LR* and *Opp* depth segregations do not agree with the perceptual structure of symmetry.
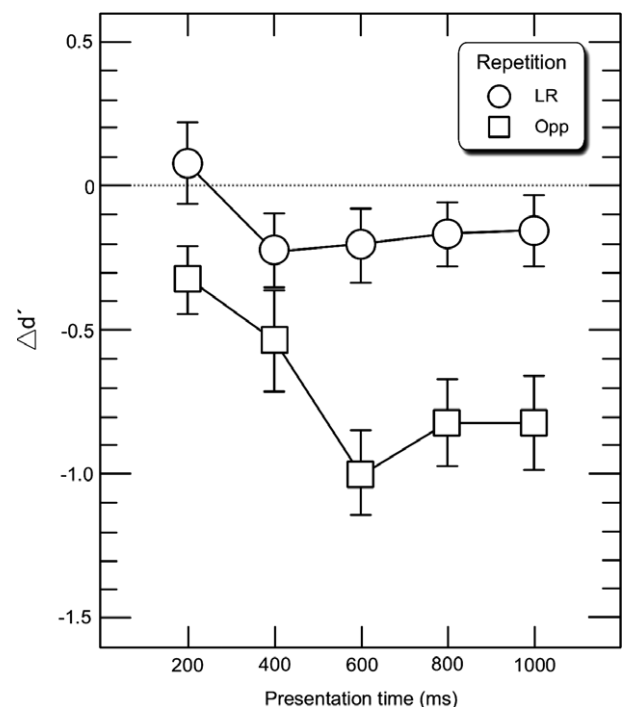

Fig. 4. Results of Experiment 1b: $\Delta d'$ on repetition as a function of presentation time. Just as for symmetry, the *Opp* curve (□) drops with increasing presentation time and then levels off, but the *LR* curve (○) is hardly affected by presentation time. This suggests that the *Opp* segregation does not agree with the perceptual structure of repetition but that the *LR* segregation does.

$t(21) = -2.313$, $p < .05$, respectively; if the 400 ms condition was removed from the analysis, the main effect disappeared ($p = .57$).

2.3. Discussion

To allow a comparison between symmetry and repetition across different presentation times, we introduced $\Delta d'$ as a measure of relative detectability, specifying d' in the *LR* and *Opp* conditions relative to the baseline. Because the effects of both prolonged viewing and target-noise separation are eliminated by this measure, any remaining effect can be attributed to the kind of manipulation applied to the stimuli. For both symmetry and repetition, we found that detection is impaired more in the *Opp* condition than in the *LR* condition. These differences are also reflected in the patterns of interaction between regularity and depth over time.

For symmetry, we found significant time effects for both kinds of manipulations (see Fig. 3). From 200 to 400 ms, relative performance drops in both conditions. After that, however, the curves for *LR* and *Opp* diverge. For *Opp*, the low relative performance at 400 ms persists, but for *LR*, relative performance recovers nearly to the level it had at 200 ms. For repetition, we only found a time effect in the *Opp* condition, where relative performance declines from 200 to 600 ms and then levels off. Although the performance drop is less severe than it is for the *Opp* condition in symmetry, the course of relative performance across presentation time is comparable for both regularities. This suggests that the stimulus segmentation triggered by the depth segregation in the *Opp* condition is compatible neither with the perceptual structure of symmetry nor with the perceptual structure of repetition. Conversely, in the *LR* condition, repetition shows no time effect, whereas symmetry does; this suggests that the stimulus segmentation triggered by the depth segregation in the *LR* condition agrees with the perceptual structure of repetition but conflicts with the perceptual structure of symmetry.

Our finding in the *LR* condition seems a stereoscopic analogue of Corbalis and Roldan's (1974) finding that separating pattern halves within the projection plane enhances the detectability of repetition but impairs the detectability of symmetry. However, in our experiment, repetition in the *LR* condition was detected not better but actually slightly worse than in the baseline condition. This raises the question of whether, compared to the baseline condition, the *LR* condition might be more complex just because it contains an additional depth plane. Another question is whether, for symmetry, the performance dip in the *LR* condition is due to the depth segregation *per se* or due to a conflict with the perceptual structure of symmetry. These two questions were investigated further in Experiments 2a and 2b, in which the *LR* condition was contrasted to a condition in which structurally corresponding elements were assigned corresponding disparity values, yielding two depth planes featuring one regularity each.

3. Experiments 2a and 2b

3.1. Methods

3.1.1. Participants, apparatus, and procedures

Twenty-one subjects participated in Experiment 2a (on symmetry) and 20 subjects participated in Experiment 2b (on repetition). None of them had participated in Experiments 1a or 1b; 11 of the subjects in Experiment 2a had participated first in Experiment 2b, but a post-hoc analysis showed no significant difference ($p = .908$) in performance between this group and the naive subjects. The parameters of the apparatus and the procedure were the same as in Experiments 1a and 1b.

3.1.2. Stimuli

Just as in Experiments 1a and 1b, we created the *Base* condition (with one regularity in one target plane) and the *LR* condition (with one half of a regularity in one target plane and the other half in the other target plane). The *Opp* condition, however, was now replaced by the *Mat* (matched) condition in which structurally corresponding elements had the same disparity, yielding two planar regularities, one in each target plane (see Fig. 2b). To the task, one of the planes was redundant because regularity could be judged on the basis of only one plane, so that the presence of an additional depth plane was the main difference with respect the baseline condition.

3.2. Results

For each experiment separately, we again calculated d' for every combination of presentation time and pattern type. Also this time, all manipulations caused a significant deterioration in performance compared to the baseline. For symmetry, repeated measures ANOVAs yielded $F(1, 20) = 11.969$, $p < .01$, and $F(1, 20) = 5.396$, $p < .05$, for *LR* and *Mat*, respectively. For repetition, the corresponding values were $F(1, 19) = 17.302$, $p < .001$, and $F(1, 19) = 20.561$, $p < .001$. As before, a more interesting analysis involved repeated measures ANOVAs performed on $\Delta d'$ to compare the effects of the manipulations with each other.

3.2.1. Effects of pattern type

For symmetry, participants performed significantly better in the *Mat* condition than in the *LR* condition, $F(1, 20) = 4.627$, $p < .05$ (see Fig. 5). The difference between *LR* and *Mat* was not significant at 200 ms ($p = .965$), 800 ms ($p = .523$), and 1000 ms ($p = .457$), but was significant at 400 ms, $t(20) = 2.926$, $p < .01$, and at 600 ms, $t(20) = 2.189$, $p < .05$. For repetition, no significant difference between *LR* and *Mat* was found ($p = .741$; see Fig. 6).

3.2.2. Time effects

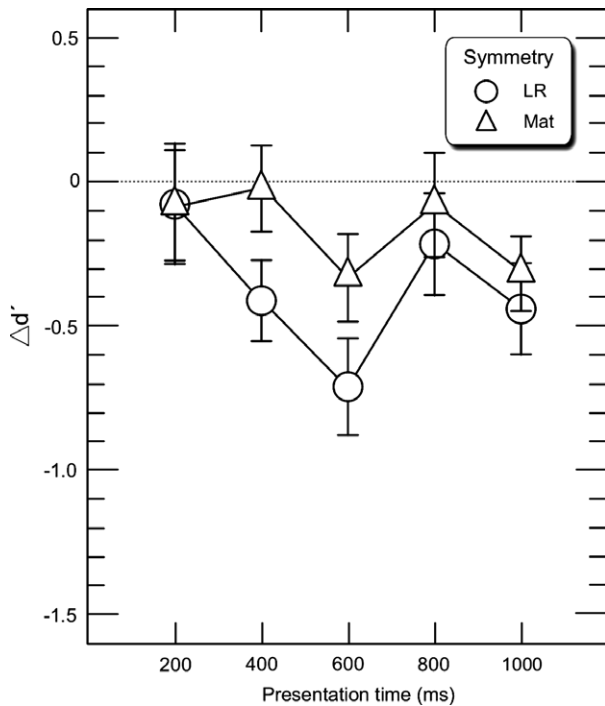There were no significant time effects for both manipulations of both regularities. However, in the *LR* condition,

Fig. 5. Results of Experiment 2a: $\Delta d'$ on symmetry as a function of presentation time. The *LR* curve (○) shows a performance dip at 600 ms. The *Mat* curve (△) has as similar slope, but there is no dip. The fact that *Mat* > *LR* suggests that symmetry is more salient when there are structural correspondences within depth planes.
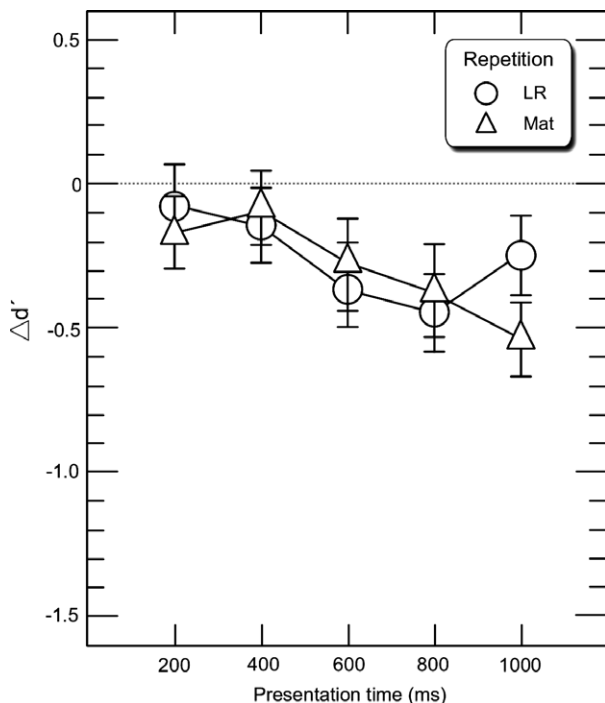

Fig. 6. Results of Experiment 2b: $\Delta d'$ on repetition as a function of presentation time. Both curves are hardly affected by presentation time. The fact that *Mat* ≈ *LR* suggests that repetition, unlike symmetry, does not depend on structural correspondences within depth planes.

two-sided *t*-tests for symmetry revealed a dip in performance just as observed in Experiment 1a. From 200 to

600 ms, performance dropped significantly, $t(20) = 2.674$, $p < .05$; subsequently, performance increased nearly significantly from 600 to 800 ms, $t(20) = -2.23$, $p = .051$. Such a dip was absent in the *Mat* condition.

3.3. Discussion

The stimuli in the *Mat* condition are similar to those in the *Base* condition in the sense that regularities are confined to single planes, but the stimuli in the *Mat* condition have two target planes while those in the *Base* condition have only one. The worse performance in the *Mat* condition relative to the *Base* condition suggests therefore that the addition of an extra depth plane *per se* increased task difficulty (the *Mat* stimuli also have fewer elements per plane than the *Base* stimuli but, if anything, we think this would give *Mat* an advantage rather than a disadvantage over *Base*). This implies that the *Mat* versus *LR* comparison is most appropriate to pinpoint differences between symmetry and repetition, because both *Mat* stimuli and *LR* stmuli contain two target planes (with the same number of elements per plane).

For symmetry, we found that *Mat* > *LR* in terms of relative performance. This suggests that symmetry detection is at its best whenever structurally corresponding elements are in the same depth plane. Furthermore, relative performance in the *Mat* condition showed no time effect, while for LR, we again found a performance dip as also observed in Experiment 1a (this time, it occurs at 600 ms instead of 400 ms). The absence of a time effect for *Mat* suggests that the presence of two target planes *per se* is not enough to trigger such a performance dip. Rather, the re-occurring performance dip for *LR* supports our earlier suggestion that such a dip occurs only when the stimulus segmentation triggered by depth cues disagrees with the perceptual structure of symmetry. The dip, and the varying presentation time it occurs at, also indicate that depth perception and symmetry perception interact in a dynamic way.

For repetition, we found that *Mat* ≈ *LR,* even though inspection of one plane sufficed in the *Mat* condition, whereas participants were forced to compare pattern halves across two planes in the *LR* condition. This supports our earlier suggestion that the stimulus segmentation triggered by the depth segregation in the *LR* condition agrees with the perceptual structure of repetition. Thus, overall, repetition detection is more robust to depth segregation than symmetry detection is.

4. General discussion

Marr (1982) argued that a full understanding of a perceptual phenomenon requires an combination of complementary approaches at three different levels of description, namely the computational level, the algorithmic level, and the implementational level. More generally, these levels can also be called the goal level, the method level, and the means level, respectively, so that the combi-

nation can be said to give an understanding of how the goal is reached by a method that is allowed by the means (cf. van der Helm & Leeuwenberg, 2004). In accordance with this scheme, we next discuss the mental representation of visual regularities (computational level), the microgenesis of visual regularity in depth, both empirically and theoretically (algorithmic level), and evidence from neuroimaging studies on the possible interaction of visual regularity and stereoscopic depth (implementational level).

4.1. Computational: The mental representation of regularity

In the traditional transformational approach, visual regularities are conceived as configurations that are invariant under motion, that is, under rigid translations or rotations (Garner, 1974; Palmer, 1983). For instance, a mirror symmetry is invariant under a 3-D rotation about the symmetry axis, and an infinite repetition is invariant under a translation the size of one repeat. Because symmetry halves and repeats, respectively, are identified with each other by these transformations, both symmetry and repetition are thus predicted to have a representation involving a block structure (see Fig. 7a and b). As a consequence, the transformational approach predicts equivalent goodness effects for symmetry and repetition. However, this is contradicted by virtually all comparative studies.

More recently, based on a mathematical formalization of regularity (van der Helm & Leeuwenberg, 1991), the holographic approach proposed to conceive visual regularities as configurations that are invariant under growth (van der Helm & Leeuwenberg, 1996, 1999, 2004). To put it simple, a repetition remains a repetition when expanded by one repeat, and a symmetry remains a symmetry when expanded by one symmetry pair. Because repeats and symmetry pairs, respectively, mark the size of the expansion steps, repetition is again predicted to have a representation involving a block structure but, this time, symmetry is predicted to have a point structure (see Fig. 7c and d). As corroborated by a quantitative goodness model (van der Helm & Leeuwenberg, 1996), this difference in representational structure agrees with many goodness effects reported in the literature, such as the higher saliency of symmetry and its greater resistance to perturbation in comparison to repetition.

Although stereoscopic factors lie outside the scope of both approaches, we can nevertheless examine whether the effects of the manipulations in our experiments agree with their basic tenets. For the transformational approach, this is not the case, because it predicts equivalent representational structures for symmetry and repetition. After all, our results suggest that the *LR* segregation agrees with the perceptual structure of repetition but not with the perceptual structure of symmetry. This finding is compatible with the holographic approach. The holographic point structure of symmetry, on the one hand, implies that a planar symmetry is built from many relationships between symmetrically positioned elements, which suggests a strong binding between the pattern halves; the holographic block structure of repetition, on the other hand, implies that a planar twofold repetition is built from only one relationship between two repeats, which suggests a segmentation rather than a binding between the pattern halves (for more details on this, see van der Helm & Leeuwenberg, 1996). This implies that the depth segregation between the pattern halves in the *LR* condition goes against the holographic structure of symmetry but not of repetition.

The difference between the holographic structures of symmetry and repetition agrees with the idea that, to perceptual organization, symmetry is a cue for the presence of one object, whereas repetition is a cue for the presence of multiple objects. This idea already has been around for a while but, so far, the empirical evidence was weak. As we mentioned in the Introduction, Baylis and Driver's (1995, 2001) and Bertamini et al.'s (1997) seemingly supporting evidence is confounded by the usage of anti-symmetry and anti-repetition as controls (see Fig. 1). Only Corbalis and Roldan's (1974) separation of the pattern halves in the projection plane can be said to yield supporting evidence, although their manipulation of the physical distance between corresponding elements in a stimulus is somewhat at odds with the idea of perceived objectness. We now found that efficient detection of symmetry but not of repetition depends on structural correspondences within depth planes. We think this provides stronger evidence for the idea of perceived objectness, because in our stimuli, we manipulated not the physical distance but the perceived distance between corresponding elements in a stimulus (i.e., the depth planes were perceived depth
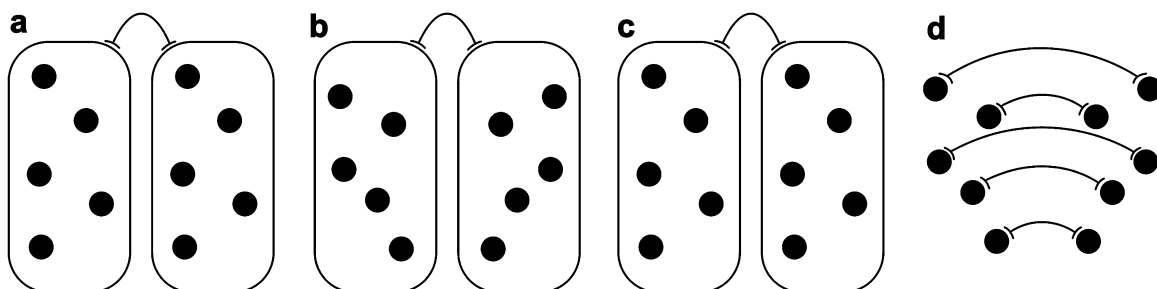

Fig. 7. Structural relationships in symmetry and repetition. According to the transformational approach, both repetition (a) and symmetry (b) have a block structure. According to the holographic approach, repetition has a block structure (c) but symmetry has a point structure (d).

planes). This implies that any grouping or segmentation is solely due to internal perceptual organization processes (for a similar argument, see Khuu & Hayes, 2005). Next, we go into more detail on these processes.

4.2. Algorithmic, part 1: The microgenesis of regularity

Symmetry detection is feasible under presentation times as short as 10 ms (Locher & Wagemans, 1993), and virtually all studies on symmetry perception use short presentation times, say, 50–150 ms (e.g., Barlow & Reeves, 1979; Carmody, Nodine, & Locher, 1977; Csathó et al., 2003; Julesz, 1971; Locher & Wagemans, 1993). In comparison to symmetry detection, the processing of relative disparity (disparity between objects) lags behind, becoming effective for exposures of 120 ms or longer (Ritter, 1980). Hence, for short presentation times, one would expect the symmetry percept to be based on the retinal image alone. Our data support this hypothesis. Although the *LR* and *Opp* manipulations yield substantially different depth percepts, there is no difference in performance at 200 ms presentation time. This is plausible considering that, at the retinal level, the *LR* and *Opp* manipulations yield parafoveal symmetries with equal eccentricity. This is shown next.

Assume that, in a symmetry, $P(x, y)$ and $P'(-x, y)$ specify the mirror-symmetric points in a coordinate frame in which the symmetry axis coincides with the *y*-axis. Suppose that, for every symmetry pair, one of the points is horizontally shifted by adding a constant *c* to its *x*-coordinate. The pattern then still has one symmetry axis but, now, located eccentrically at $x = c/2$ irrespective of whether the shifted points all lie on one side of the pattern (as occurs in the *LR* condition) or are distributed across both sides (as occurs in the *Opp* condition). In the *Mat* condition, conversely, one half of the symmetry pairs are shifted and the other half of the symmetry pairs are left at their original position. This yields two symmetries, one fovea-centered symmetry and one symmetry located eccentrically at $x = c/2$. The percept thus boils down to a jittered foveal symmetry, but compared to *LR* and *Opp*, the saliency-increasing (foveal symmetry) effect probably cancels out the saliency-decreasing effect (jitter). In total, this suggests that $LR \approx Opp \approx Mat$, which is what we found. In other words, the effects on symmetry at 200 ms can be accounted for in terms of the retinal image. This also implies, however, that the subsequent divergence of the *LR* and *Opp* curves is not explicable in terms of the retinal image. The re-occurring performance dip in the *LR* condition must be an effect of stereo processing, because the *LR* and *Opp* stimuli do not differ before disparities have been processed.

In repetition, a basic characteristic is that the intra-pair distance between corresponding elements is the same, say *D*, for all pairs. At the retinal level, the *LR* segregation corresponds to a shift of the left-hand or right-hand half of the pattern, which either increases or decreases the intra-pair distance for all pairs by the same amount, that is, the new intra-pair distance is again the same for all pairs. By

the *Mat* segregation, repetition pairs are shifted, so that, again, the intra-pair distance remains the same for all pairs. The *Opp* segregation, however, does not preserve this characteristic. In one half of the pairs, the left-hand element is shifted, say by a horizontal distance *c*, yielding a new intra-pair distance of $D - c$; in the other half of the pairs, the right-hand element is shifted, yielding a new intra-pair distance of $D + c$. In total, this suggests that $Mat \approx LR > Opp$, which is what we found not only for short presentation times but also for longer ones.

Hence, our data suggest that regularity detection shifts from a retinal frame of reference to a stereoscopic frame of reference. This indicates a genuine interaction between regularity cues and depth cues, that is, not merely an interference of regularity detection by stereo processing. This is clear for repetition: spreading structurally corresponding elements across depth planes does not necessarily hinder the repetition percept. Rather, the detectability of repetition depends on whether the depth segregation agrees with the perceptual structure of repetition. Next, we discuss this issue more theoretically.

4.3. Algorithmic, part 2: Regularity-detection anchors in depth

Jenkins (1983) proposed that the regularity-detection mechanism uses virtual lines between corresponding elements as the first-order anchors to propagate from. In both symmetry and repetition, these virtual lines exhibit orientational uniformity; in addition, the virtual lines are midpoint collinear in symmetry and have a constant length in repetition. Wagemans (Wagemans, 1995; Wagemans, van Gool, & d'Ydewalle, 1991; Wagemans, Van Gool, Swinnen, & Van Horebeek, 1993) noticed that orientational uniformity and midpoint collinearity also hold for the virtual lines in skewed symmetry which, nevertheless, is less salient than non-skewed symmetry. He therefore proposed additional second-order anchors in the form of trapezoids (in symmetry) and parallelograms (in repetition), composed of two virtual lines each. These second-order anchors are distorted by skewing, which explains the lesser saliency of skewed symmetry. Because the first-order and second-order anchors as such do not yet explain that symmetry is more salient than repetition, van der Helm and Leeuwenberg (1999) proposed in addition that symmetry detection propagates exponentially but that repetition detection propagates linearly (they inferred this directly from the holographic approach in van der Helm & Leeuwenberg, 1996).

So far, the foregoing ideas about first-order and second-order anchors have been applied only to retinal projections of visual regularities. The question now is whether these ideas are consistent with our findings for regularities in stereoscopic space. Because both midpoint co-planarity (the 3-D analogue of 2-D midpoint collinearity) in symmetry and constant length in repetition are preserved under all three stereoscopic manipulations, these segregations should manifest themselves in violations of the first-order orienta-

tional uniformity or in perturbations of the second-order anchors.

4.3.1. Symmetry

In both *LR* and *Opp* stimuli, structurally corresponding elements are spread across two depth planes. The angle of a virtual line relative to the frontal plane is larger the closer the elements are to the symmetry axis. Therefore, both *LR* and *Opp* stimuli violate orientational uniformity. In *LR* stimuli, the angles of all virtual lines are either positive or negative while, for *Opp* stimuli, both positive and negative angles occur. Hence, the degree of violation is higher for *Opp* than for *LR*. In *Mat* stimuli, all angles are zero, thus preserving orientational uniformity, and only in *Mat* stimuli, the second-order trapezoids remain intact. In total, this suggests that *Mat > LR > Opp,* which is what we found for presentation times of 400 and 600 ms.

4.3.2. Repetition

In *LR* stimuli, all virtual lines have the same angle relative to the frontal plane, thus preserving orientational uniformity. In *Opp* stimuli, orientational uniformity is violated, because both positive and negative angles occur. In *Mat* stimuli, all angles are zero, thus again preserving orientational uniformity. Furthermore, in *LR* and *Mat* stimuli but not in *Opp* stimuli, the second-order parallelograms remain intact. In total, this suggests that *Mat ≈ LR > Opp*, which is what we found for presentation times of 200–800 ms.

The preceding analysis shows that our findings for regularities in stereoscopic space can be understood by considering the proposed first-order and second-order anchors of the regularity-detection mechanism in a stereoscopic frame of reference. This gives further support to the idea of a genuine interaction between regularity cues and depth cues. In the next subsection, we review neuroimaging studies on stereopsis and regularity processing to examine the neural plausibility of such an interaction between regularity and depth cues.

4.4. Implementational: Neural interaction of regularity and depth

Stereopsis cannot be pinpointed to be implemented in a specialized neural location. Rather, stereopsis-related activation has been found in many areas, such as V3, V3A, MT+, and parietal regions (e.g., Fortin, Ptito, Faubert, & Ptito, 2002; Gulyás & Roland, 1994; Merboldt, Baudewig, Treue, & Frahm, 2002). However, peak activation is usually found in extrastriate areas V3 and V3A (Backus, Fleet, Parker, & Heeger, 2001; Gillaie-Dotan, Ullman, Kushnir, & Malach, 2002; Kourtzi & Kanwisher, 2001; Kwee, Fujii, Matsuzawa, & Nakada, 1999; Mendola, Dale, Fischl, Lui, & Tootell, 1999; Negawa et al., 2002; Ptito et al., 1993). Furthermore, there seems to be a neural differentiation between absolute disparity processing and relative disparity processing. While dorsal areas V3A, MT+ and V7 code absolute disparity but not relative disparity, ventral areas hV4 and V8 are sensitive to both (Neri,

Bridge, & Heeger, 2004). Single-cell studies in monkeys support the involvement of higher ventral stream areas in disparity-defined shape processing (e.g., Janssen, Vogels, Liu, & Orban, 2003; Janssen, Vogels, & Orban, 2000a, Janssen, Vogels, & Orban, 2000b). Finally, Brouwer, van Ee, and Schwarzbach (2005) found transient activation in areas V4d-topo, V3A, and V7, correlated with the onset of stereoscopic perception. They also found sustained activation in areas V4v, VP, and LOC, correlated with the stereoscopic percept. They proposed that the latter areas code for shapes defined by disparity.

In contrast to stereopsis, regularity detection has only recently become a topic in neuroimaging. While an initial study reported DLO (dorsolateral occipital cortex) to be involved in symmetry perception (Tyler et al., 2005), a follow-up study reported a more distributed pattern of activation (Sasaki, Vanduffel, Knutsen, Tyler, & Tootell, 2005). That is, this follow-up study reported high levels of activation in V3A, V4, V7, and LOC, marginal activation in V3, and virtually no symmetry-specific activity elsewhere. More recently, Chen, Kao, and Tyler (2007) showed that frontally viewed faces also increase activation in these areas relative to their phase-scrambled versions, and they argued that these areas may also feed the adjacent OFA (occipital face area), which seems to be involved in processing specific to facial symmetry.

Evidently, there are common sites of activation for processing related to stereopsis and symmetry detection, namely, extrastriate area V3A and ventral stream area LOC. Symmetry detection could be mediated by stereoprocessing directly via interactions in these regions, or indirectly via feedback loops to V1.

To elaborate on the latter, Lee, Mumford, Romero, and Lamme (1998) proposed that V1 might serve as a high resolution buffer used for computations by extrastriate visual areas. This suggests that recurrent feedback from stereoprocessing in V3A might be relayed to symmetry processing areas via V1. This does not seem very plausible, however. First, so far, neuroimaging studies did not report V1 activation related specifically to symmetry detection. Second, although V3A showed the strongest response in stereoprocessing, it codes only absolute disparity, but relative disparity processing is needed in our stimuli.

In contrast, LOC is associated with object perception (Grill-Spector, 2003; Malach et al., 1995) and, as mentioned, it has been proposed to be involved in coding disparity-defined shapes. This makes LOC a good candidate for the locus of symmetry–depth interaction. The foregoing suggests that this interaction might take the form of a direct competition between the stimulus interpretation defined by disparity versus the stimulus interpretation defined by regularity.

5. Conclusions

Regularity and depth are not processed one after the other. We presented psychophysical, theoretical, and neu-

rofunctional evidence that both regularity detection and stereo processing are ongoing processes that interact dynamically over time. During this interaction, the detection of symmetry and repetition shifts from a retinal frame of reference to a stereoscopic frame of reference, yielding effects that depend on the regularity at hand. That is, efficient detection of symmetry depends on structural correspondences within depth planes, but efficient detection of repetition does not. This confirms the idea that, to perceptual organization, symmetry is a cue for the presence of one object, whereas repetition is a cue for the presence of multiple objects.

Acknowledgments

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