Anuario de Psicología
2011, vol. 41, nº 1-3, 9-20

The influence of background topography on stereo-acuity[*]

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Human depth perception can be strongly affected by the characteristics of the environment. Previous studies have assessed visual acuity in the fronto-parallel plane but little is known about the effect of background topography on stereoacuity. In the present experiment, based on alignment tasks, we analyzed how stimulus orientation and 3D background configuration influence stereoscopic vision. An experiment was designed to investigate the influence of stimulus orientation (0, 45 and 90 degrees) and background configuration (flat, black, concave and convex) on precision in 3D visual alignment tasks in a virtual environment. Background was found to result in an underestimation of stereo-acuity, with the highest and lowest precision scores in comparison judgment tasks corresponding to convex and concave backgrounds, respectively. In addition, a significant orientation by background interaction was discovered. We conclude that background local depth cues are integrated with our target stimuli to contribute to depth perception

Key words: *depth perception, figure-background relationship, stereo-acuity, Vernier visual acuity, visual psychophysics.*

Influencia de la topografía del fondo sobre la estéreo-agudeza

Las características del medio pueden influir notablemente en la percepción de la profundidad en humanos. Estudios previos han evaluado la agudeza visual en el plano fronto-paralelo sin embargo, desconocemos cómo

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[*] This work was supported by a grant PSI2009-11062-PSIC from the Spanish Ministry of Education and Science (MICINN).
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la topografía de fondo, contra el que se muestra el estímulo, afecta a la agudeza estereoscópica. Hemos diseñado un experimento, en el que aplicamos a los sujetos una tarea de alineación visual, a partir de esta, examinamos cómo la orientación del estímulo y el tipo de relieve de una superficie 3D usada como configuración de fondo, altera la agudeza estereoscópica. Mediante el método de estímulos constantes, investigamos la influencia de la orientación del estímulo (grados 0, 45 y 90) y la configuración de fondo (plano convexo, negro, y cóncava) sobre la precisión en los juicios de alineación visual 3D en un entorno virtual. Los resultados mostraron que el fondo provocaba cierta tendencia a la subestimación de la estéreo-agudeza, obteniéndose las puntuaciones máximas y mínimas, en cuanto a precisión, en los juicios correspondientes a los fondos convexo y cóncavo, respectivamente. Además, el análisis estadístico reveló una interacción significativa entre "orientación x fondo". Concluimos que las claves locales de profundidad de la superficie de fondo se integran con los estímulos que debían alinearse para contribuir a la percepción de profundidad.

Palabras clave: *percepción de la profundidad, relación figura-fondo, estéreo-agudeza, agudeza visual de Vernier, psicofísica visual.*

Introduction

Natural environments provide multiple simultaneous visual cues, many of which are partially redundant and profoundly and intricately interconnected, that contribute to depth perception, allowing for the integration and combination of diverse information sources, as well as for the possibility of discordance, which may lead to perceptual biases or distortions (Cutting & Vishton, 1995; Watt, Akeley, Ernst & Banks, 2005). Recent years have witnessed an increasing interest in the mechanisms provided by of our visual system to deal with this multiplicity of visual cues (Landy, Maloney, Johnston & Young, 1995; Sedgwick, 2001).

Several authors have explored the interaction of surface characteristics with spatial information integration. Doumen, Kappers and Koenderink (2008) described an influence of the background surface in a scene on the perception of the exocentric direction between two test-objects when that surface served as a reference in the task. Similarly, in a previous study by Mitchison and Westheimer (1984), background surface slant was found to influence depth perception of stimuli situated in front of it. Other authors explored the effect of binocular disparity with regards to a plane of reference, disclosing significant associations between depth perception thresholds and both absolute and relative stimulus disparities (Andrews, Glennerster & Parker, 2001; Glennerster & McKee, 2004; Petrov & Glennerster, 2004, 2006).

Following a parallel approach, Knill and Saunders (2003) described the mechanisms by which humans employ an optimal combination of disparity and texture cues to influence surface slant judgments, with cue weights proportional to the subjective reliability of these cues. Mather and Smith (2004) evaluated the relative contribution of contrast, blur and occlusion cues in depth perception, evidencing an improvement in depth judgments when all three cues were simultaneously present, thus suggesting a possible summation between depth cues extracted by independent processes.

Visual acuity (VA) is the ability to discriminate fine details of an object in the visual field. Therefore, it is a measure of visual function or visual quality. In central vision, VA is ultimately limited by the separation between cones, whereupon it varies with retinal eccentricity and pupil size. Vernier acuity is the ability to detect subtle differences in a straight alignment, so it is also known as the power of alignment. Alignment tasks are employed to evaluate Vernier acuity. To the best of our knowledge, precision in alignment tasks consisting of multiple targets located on different depth planes has not been extensively studied. Indeed, although Heinrich, Kromeier, Bach and Kommerell (2005) disclosed a reduction in Vernier visual acuity with increasing binocular disparities, the question of how background influences stereoacuity measurements remains unresolved.

The present study aimed at investigating the influence of background characteristics on the ability of observers to perform depth judgment tasks in a virtual environment promoting an impression of relative depth. Dichoptical presentation of target stimuli was accomplished with a pair of liquid crystal shutter stereoscopic glasses, thus allowing for fine-grain discrimination (very small range of depth intervals). Precision was therefore assessed in a short-range space and the results served to explore the mechanisms for integration and segregation of figure *versus* background cues. The observers were required to assess depth intervals between target stimuli presented over different three dimensional (3D) shaped backgrounds. In addition, three different target stimuli orientations were evaluated in order to investigate any possible background-stimulus orientation interaction.

Method

Participants

A total of 10 subjects (6 female; 4 male), with ages ranging from 32 to 47 years (Mean = 40.7 years; *SD* = 6.0 years) participated in the study. All participants had best distance corrected decimal visual acuity of 1 or better and stereoacuity of at least 30 seconds of arc (as measured with the TNO test). All participants provided written informed consent after the nature of the study had been explained to them. The Declaration of Helsinki tenets of 1975 (as revised in Tokyo in 2004) were followed throughout the study, which received clearance by the Ethics Committee of the Universitat de Barcelona.

Stimulus and apparatus

Stimuli generation and presentation was governed by a 2.66 GHz Intel® Pentium® IV personal computer equipped with an Nvidia® Quadro® FX 3500 graphics processing card. A 22-inch CRT Samsung® Syncmaster® 1100 DF monitor at 2048 x 1536 resolution and 120 Hz refresh rate was employed for stimuli presentation, the temporal characteristics of which were defined with the C++ Programming Language, with the OpenGL® GLUT32 graphic library utility generating the required 3D stimuli. In order to achieve a refresh rate of 120 Hz, the LCD shutter glasses made transitions at a speed of 8.33 ms. Precise observation distance from the monitor (100 cm) was ascertained with the use of a head and chin rest, which also prevented head tilting. A pair of liquid crystal shutter stereoscopic glasses (CrystalEyes®) was employed during the experimental setting.

Target stimuli consisted in two parallel line segments in dichoptical presentation, thus allowing for different relative positions of each line in the frontoparallel plane for each eye, resulting in binocular disparity between line segments and the impression of depth. The reference stimulus for the experimental setting consisted of two parallel red line segments, 1 mm thick and 50 mm long, presented over a background. Average luminance of the line segments was of 15 cd/m^2 (as measured with a Minolta LS-100 luminance meter). Line segments had a horizontal separation (ΔH) of 15 mm, a vertical separation (ΔV) of 16 mm and a depth interval (ΔZ) of 20 mm for 0 degree orientated lines (see Figure 1). In order to manipulate the orientation of the stimulus, two additional reference stimuli (for 45 degrees and for 90 degrees oriented lines) were generated by rotating the previous stimulus counterclockwise in the frontoparallel plane. Dichoptical presentation allowed for each line segment to be seen with one eye only, with their fusion resulting in depth perception.

Observation distance remained constant at 1000 mm, which corresponded to the distance between the observer and the first segment line. As for the reference stimulus, the second segment line was presented 20 mm behind the first one, that is, 1020 mm from the observer.

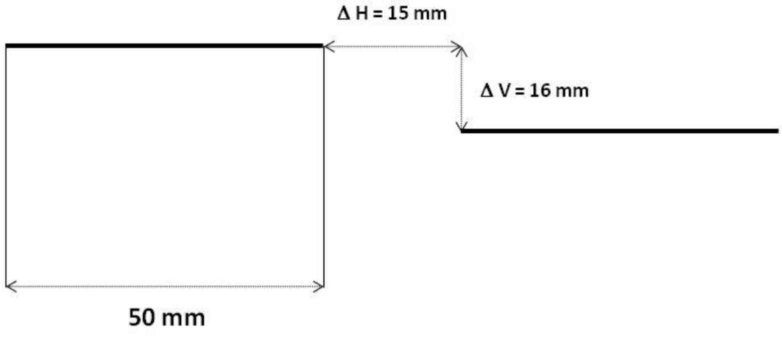

Figure 1. Frontal view of the reference stimulus with a 0 degrees orientated segment line (the 20 mm depth interval is not observable).

The comparison stimuli for each orientation differed from the reference stimulus in their depth interval, which ranged from 12 to 28 mm, in 2 mm steps. Therefore, the distance between the observer and the second segment line of the comparison stimuli varied between 1012 and 1028 mm, resulting in nine different depth intervals for the comparison stimuli (see table 1 for the corresponding angle, in seconds of arc, for an observation distance of 1000 mm). Besides, for each depth interval, comparison stimuli were generated for 45 degrees and 90 degrees oriented lines.

TABLE 1. COMPARISON STIMULUS (IN MM AND SEC ARC) FOR A VIEWING DISTANCE OF 1000 MM

Viewing distance to the second segment line of the comparison stimuli (mm)	*Depth interval between both segment lines of the comparison stimuli (sec arc)*
1012	1528.6
1014	1525.6
1016	1522.4
1018	1519.6
1020	1516.6
1022	1513.7
1024	1510.7
1026	1507.7
1028	1504.8

In order to investigate the influence of background, as well as stimuli orientation, on the performance of the observers, both reference and comparison stimuli were presented over black, flat, concave or convex backgrounds. Concave and convex backgrounds corresponded to Bézier surfaces, and were generated with the C++ Programming Language and OpenGL® (Silicon graphics Inc.). Thus, the Bézier surface associated with a set of points (P_{ij}) is defined by:

$$S(u,v) = \sum_{i=0}^{m}\sum_{j=0}^{n} P_{ij}\, B_i^m(u) B_j^n(v)$$

where $B_i^m(u)$ and $B_j^n(v)$ represent the Bernstein polynomials of degrees *m* and *n* for the parametric coordinates *u* and *v*, respectively. Both concave and convex surfaces were determined by the same control points, as was the flat background, thus ensuring an identical grid configuration (yellow in color and with an average luminance of 30 cd/m^2). Thus, the only available light source was the screen which presented stimuli to the observers, with an average luminance of 45 cd/m^2 (15 cd/m^2 provided by the figure and 30 cd/m^2 by the background). All backgrounds (except "black") had an area of 250 x 250 mm (corresponding to a visual angle of 14.25 degrees for an observation distance of 1050 mm) and were presented at 50 mm behind the first segment line, centered on the observer (figure 2). Therefore, with addition to convex and concave backgrounds there were two neutral conditions acting as control backgrounds in our study, using as background either a flat surface (zero curvature) or a "black screen" (background absence experimental setting), without defined limits (although circumscribed to the surface of the screen).

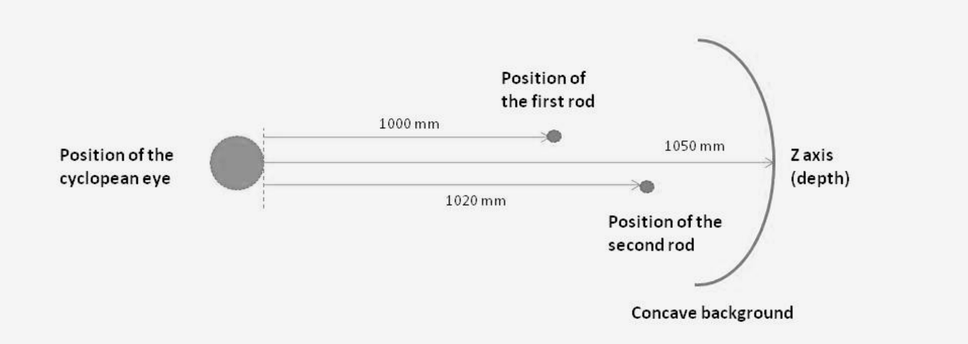

Figure 2. A sketch of the reference stimulus and background position for a concave surface configuration.

Procedure

Participants were allowed to gain familiarity with the experimental settings and procedure, and a minimum of 10 training trials were conducted. A psychophysical method of constant stimuli was implemented, with a forced-choice between two different options: depth distances of the comparison stimuli (Cmp) were larger of shorter than those of the reference stimulus (Ref). Each experimental trial started by the presentation of the reference stimulus, followed by the comparison stimulus. Presentation time was adjusted at 1500 ms for both reference and comparison stimuli, with a 500 ms gap between presentations during which the monitor was black. During the task, participants were asked to judge depth interval differences (ΔZ) between the reference and the comparison stimuli and to answer by pressing the right or left mouse buttons when they perceived the comparison stimulus to have a larger (Cmp > Ref), or smaller (Cmp < Ref), dealignment than the reference stimulus, respectively. No feedback was provided in response to the participants' answers.

An intrasubject design for repeated measures was implemented, which consisted of a total of 12 possible experimental conditions resulting from a combination of two different factors: orientation of the line segments (0, 45 or 90 degrees) and background configuration (black, flat, concave or convex). Each of the possible nine relative references *versus* comparison stimuli positions was randomly presented 24 times to each participant. Visual fatigue and attention decline, which could negatively influence participants' performance, were avoided by dividing all measurements in groups of 72 trials each, and by limiting each experimental session to a maximum of three groups of trials, between which participants were allowed time to rest. Participants completed two 90 minutes experimental sessions per day until the conclusion of the study.

Data analysis

For each experimental condition, data was fitted to a gaussian cumulative function (see figure 3) in terms of the percentage of responses where participants considered the comparison stimulus to present a larger dealignment than the reference stimulus (Cmp > Ref). Precision, or discrimination finesse, was determined by transforming all percentage values to standardized (Zi) values according to their goodness of fit to the Laplace-Gauss normal distribution curve and by calculating the slope of the regression line defined by those Zi values and the value of the comparison stimulus. With this analysis, precision increases with the slope of the regression line, with a maximum value of 1.

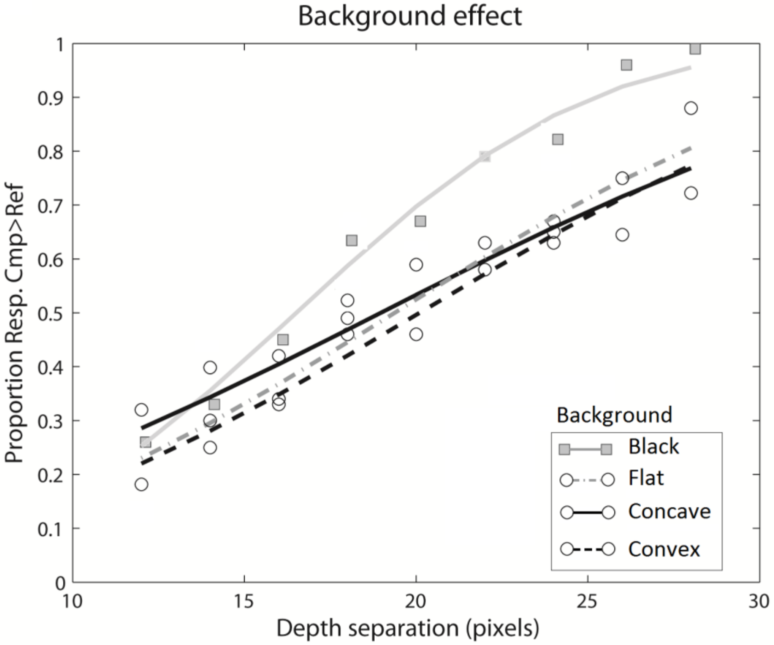

Figure 3. Cumulative Gaussian functions plotting the percentage of responses where participants considered Cmp > Ref versus *the actual misalignment values of the comparison stimulus. Four background conditions are displayed (Black, Flat, Concave and Convex).*

A repeated measures analysis of variance (ANOVA) was employed to investigate the effect of stimulus "*orientation*" and type of "*background*" (therefore 3 x 4) on precision. The Greenhouse-Geisser correction for sphericity departures was applied if necessary. A $p < 0.05$ was considered to denote statistical significance throughout the study.

Results

The values for the mean slope of the regresion lines (i.e. precision in stereo depth) for each configuration of background and stimulus orientation are provided in table 2. This table provided combined precision scores for either all orientations (background analysis) or all backgrounds (orientation analysis). Black and convex backgrounds were found to increase precision in stereo depth judgements, whereas precision with a concave background was the lowest. Orientation was also found to influence precision in stereo depth, with the highest and lowest values for 90 and 0 degrees, respectively.

TABLE 2. *PRECISION IN STEREO DEPTH FOR EACH BACKGROUND AND STIMULUS ORIENTATION CONFIGURATION (MEAN AND SE). VALUES CLOSE TO 1 ARE REPRESENTATIVE OF A STEEPER SLOPE OF THE STANDARDIZED REGRESION LINE (HIGH PRECISION).*

Factor	*Mean*	*SE*
Black background	0.466	0.009
Concave background	0.427	0.013
Flat background	0.432	0.007
Convex background	0.466	0.010
0º orientation	0.373	0.008
45º orientation	0.468	0.008
90º orientation	0.503	0.011

Precision in stereo depth were analyzed with an ANOVA by a repeated measures, with "*orientation*" (0, 45 and 90 degrees) and *"background"* (black, flat, concave and convex) as within-subject factors. The results of this analysis showed that both single effects for "*background*" [F(3,27)= 5.146; p < 0.021] and "*orientation*" [F(2,18)= 70.251; p < 0.001], as well as the interaction "*background by orientation*" [F(6,54)= 11.239; p < 0.001] were found to have a statistically significant impact on the precision in depth judgment.

The interaction *background by orientation* is displayed in figure 4. Precision in stereo depth on a convex background was found to be differently influenced by orientation than on the other studied background configurations. Indeed, whereas concave backgrounds resulted in higher precision than convex backgrounds at horizontal orientations (0 degrees), the opposite behaviour was observed at orientations of 45º. At 90º, both concave and convex backgrounds displayed similar stereo precision values (0.506 ± 0.025 and 0.507 ± 0.022, respectively).

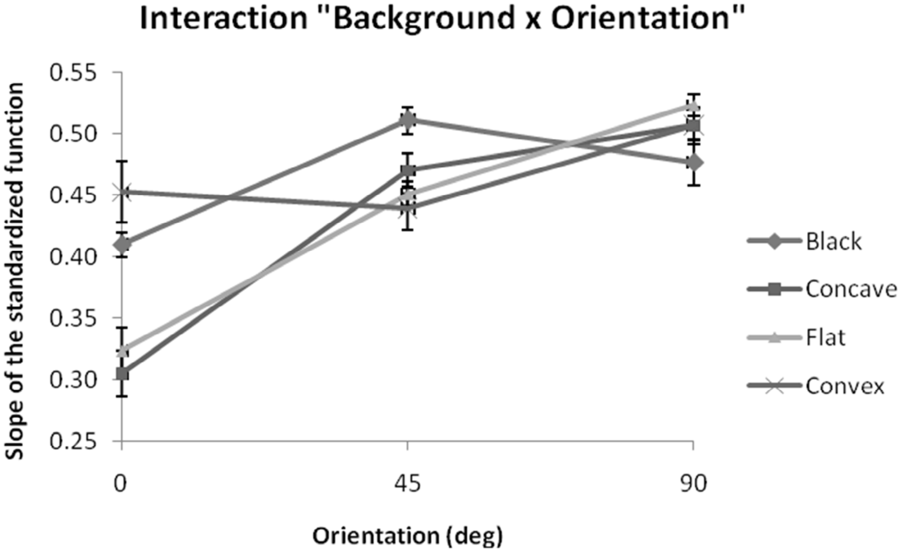

Figure 4. Mean of the slopes of the standarized coeficients in the regression line were used as dependent variable for an ANOVA. The figure show stereo precision as a function of orientation for each background condition, illustrating the background by orientation *interaction (mean and* SE *values are shown).*

Discussion

The present investigation aimed at evaluating the effect of background and orientation on the ability of observers to perform depth judgments in a virtual environment. The results of the experiment (conducted in a short-range space with depths of the comparison stimuli ranging from 1012 to 1028 mm) revealed a statistically significant negative impact of concave background on stereo precision, more manifest for the horizontal (0 degree) orientation of the line segments. These findings show an influence of background topography on precision in depth perception. Therefore, our results have important theoretical implications for a better understanding of the problem of the integration of a variety of depth visual cues. Indeed, our study has shown that, at least in virtual environments, the type of surface operating as background was influential, that is, the integration of the various levels of depth and different surface topology characteristics of these planes could modulate the assessment of visual stereo-acuity. However, these findings must be explored in terms of the differences between real and virtual environments. Thus, Loomis and Knapp (2003) reported that subjects viewing virtual environments judged distances to be shorter than when the same target stimulus was presented in real environments. Indeed, some reasons have been postulated to suggest that stereoacuity, as assessed by stereograms, differs from stereoacuity measured in more realistic conditions (higher ecological validity), thus resulting in a reduction in precision of virtual depth judgment tasks (Buckley & Frisby, 1993; Frisby, Buckley & Horsman, 1995; Porril, Duke, Taroyan, Frisby & Buckley, 2010; Watt *et al.,* 2005). These authors imply a conflict between binocular disparity, accommodation and fusional vergence in 3D virtual environments as a possible explanation of these discrepancies. Other authors (*e.g.*, Norman, Todd, Perotti & Tittle, 1996), however, reported important imprecision when participants were asked to perform tasks with real stimuli in 3D viewing conditions. Thus, the advantages and disadvantages of using virtual *versus* natural environments, as well as the inherent conflicts associated with the former, remain a legitimate subject of debate.

Recent research regarding the influence of background on the performance of various visual tasks has revealed a detrimental contribution of this factor, that is, a noise effect (McKendrick, Weymouth & Battista, 2010), with the relative spacing of the stimuli to the background noise elements also affecting contour integration (Hadad, Maurer & Lewis, 2010). An important task of our visual system is the correct detection of objects, a task requiring segregation of those objects from their backgrounds (Loffler, 2008). In the present experimental settings participants had to perform a depth judgment task while segregating the background over which the stimuli (pair of parallel lines) were observed. Our findings revealed a negative influence of concave backgrounds in stereo precision. Several authors (e.g., Glennerster & McKee, 2004; Andrews *et al.,* 2001; Petrov & Glennerster, 2004, 2006) have reported that binocular disparity with respect to a plane of reference is an important cue for stereoscopic performance. Indeed, these authors documented larger bias in depth perception with decreasing disparities between background and target stimuli. Our findings, in which concave backgrounds (larger disparities with regards to the target stimuli) resulted in a larger negative impact in the precision of depth judgment tasks than convex backgrounds, give support to these studies. However, the performance of the participants was still better when stimuli were observed over a black background, a finding that would advocate for a negative effect of any type of background on the perception of stimuli located in front of it, that is, depth perception in virtual environments is impaired by background cues.

It is interesting to note that the "black" background experimental condition was the best stereo precision trigger, with better scores than those obtained when a "flat" background was present. This finding suggests that observers conceptualize space differently according to the type of surface operating as background. That is, while "flat" background was interpreted as a limited (finite) space, "black" background (absence of background) prompted the observer to interpret it as unlimited (located at visual infinity), with obvious geometrical relevance, as a space fitted to a Euclidean geometry is infinite, while a space fitted to a curved geometry (Riemannian geometry: hyperbolic or elliptical) is limited. In summary, our data infers that observers used different metrics to compute the distance in these experimental conditions. In addition, these findings would suggest that, in order to process different depth planes, precision is lost either as a consequence of figure-background segregation (masking of background against stimuli) or of some type of conflict in accommodation arising from background disparity gradients. Further research is required to understand these findings.

However, another possible explanation for the decreased precision found on concave background may rest in the natural convexity of the retinal curvature (d'Alessandro, 2008), that is, the fact that the hemispherical form of the back of the eye prevents an isometric representation of the external world, which is spherical. Indeed, precision improved in convex backgrounds, with values very similar to those obtained in black backgrounds, therefore suggesting that the performance of our visual system during depth judgments is best when retinal and environmental curvatures are of the same sign. In addition, our findings for concave backgrounds revealed opposite precision trends only for 0 and 45 degrees and not for 90 degrees. It is however not clear why the 90 degree orientation results in a suppression of the effect of background on precision.

Finally, the interaction between *background* and *orientation* was found to have a statistically significant effect on precision. These findings suggest that each orientation is independently affected by background. An explanation of these results may reside in the integration of depth cues that occurs in 3D viewing conditions, leading background to play a role in the segregation between depth planes, maybe through an attracting effect, thus negatively impacting figure-background differentiation. This hypothesis favors the notion that our visual system employs background cues to gain information from surrounding environments.

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