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The Effects of Three-Dimensional Context on Shape Perception

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Abstract
Humans have a unique ability to perceive shape in different ways. Although we naturally estimate objective (physical) shape in our daily interactions with the world, we are also capable of estimating projective (retinal) shape, especially when attempting to accurately draw objects and scenes. In four experiments, we demonstrated robust effects of 3D context on shape perception. Using a binocular stereo paradigm, we presented rectangular surfaces of varying widths alone or embedded in a polyhedron. We investigated how context, judgment type, and angle affected width estimates. We found that the presence of even a small amount of 3D context aids objective judgments but hinders projective judgments, whereas a lack of context had the opposite effect. Context facilitated objective shape assessments by improving estimates of surface orientation. These results demonstrate that the typical presence of 3D context aids shape perception (shape constancy) while simultaneously making the projective judgments necessary for realistic drawing more difficult.

Keywords
shape constancy, shape perception, three-dimensional context, stereopsis, texture, contour, objective, projective, open data, open materials

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The influence of context on perception and memory is a cornerstone of cognitive psychology. Context facilitates object processing (e.g., Biederman, Mezzanotte, & Rabinowitz, 1982; Davenport & Potter, 2004; Oliva & Torralba, 2007; Palmer, 1975) and is important in extracting various perceptual constancies, such as size (Holway & Boring, 1941), lightness (Jacobson & Gilchrist, 1988; Wallach, 1963), and color (Land & McCann, 1971). Remarkably, there has been less systematic work addressing the effects of 3D context on shape constancy and shape perception more generally. The neural mechanisms underlying the perception of 3D shape from 2D retinal images are powerful and automatic enough that perception may seem instantaneous and effortless (e.g., Sereno, Trinath, Augath, & Logothetis, 2002). These neural mechanisms are necessary for shape constancy—the perception that rigid objects maintain their inherent physical structure and shape regardless of viewing angle (e.g., you perceive your desktop as a rectangle whether you see it from the perspective of your chair or from a bird's-eye view). The shape-slant-invariance hypothesis (Beck & Gibson, 1955; Koffka, 1935) predicts that the accuracy of objective shape perception will be dependent on the accuracy of estimates of slant.

Shape constancy is generally a helpful phenomenon that allows people to interact with objects and to navigate the visual world with relative ease. However, the strength of these mechanisms makes it hard to "unsee" the world—that is, to see the 2D projected shapes of objects. Skill in drawing depends on perceiving and accurately rendering the 2D projected image of objects as opposed to the actual 3D shape. Thus, shape-constancy mechanisms may naturally interfere with accessing two-dimensionally projected shape information (e.g., Cohen & Jones, 2008; Mitchell, Ropar, Ackroyd, & Rajendran,

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2005). The purpose of the current study, then, was to systematically investigate how 3D context affects shape perception, both the ability to accurately represent an object's actual or objective shape (i.e., shape constancy) as well as its projective shape. We hypothesized that 3D context would facilitate objective estimates of shape but hinder projective estimates.

Previous research on the perception of shape from different viewing angles has predominantly focused on estimates of projective (e.g., Thouless, 1931a, 1931b) or objective (e.g., Massaro, 1973) shape of single isolated surfaces often under reduced viewing conditions (for reviews, see Epstein & Park, 1963; Howard, 2012; Sedgwick, 1986). Thouless (1931a, 1931b), for example, found that projective judgments of inclined shapes (e.g., circles, squares) viewed binocularly lie between the objective and projective shapes, an effect he referred to as "phenomenal regression to the real object." Error in objective judgments of simple shapes viewed binocularly increases with increased slant, shifting in the direction of the projective shape (e.g., Massaro, 1973). Shape constancy is improved with better viewing conditions (binocular disparity, motion parallax), more complex shapes, and stimulus familiarity (Lichte & Borresen, 1967).

Few studies have examined the influence of context on the perception of flat rigid shapes. One study (Olsen, Pearl, Mayfield, & Millar, 1976) demonstrated that when two crossed lines positioned on the surface of a tilted rectangular box were viewed binocularly (rather than as photographic slides), relative objective-length estimates were quite accurate. In another study (Lappin & Preble, 1975), participants made objective and projective judgments of one angle of an eight-sided polygon that was placed on a desk surrounded by objects and presented as photographic slides. Judgments of both objective and projective angles were closer to the actual (objective) angle than the projective angle, which indicates a degree of shape constancy irrespective of judgment type.

Several other studies have investigated the relationship between projective shape judgments in the presence of context and artistic drawing ability (e.g., Cohen & Jones, 2008; Mitchell et al., 2005). Mitchell et al. (2005) found that errors in both the perception and drawing of two parallelograms were greater when context (perspective cues in the form of table legs) was added. Cohen and Jones (2008) asked participants to choose the projective shape, presented as outlines, that matched the shape of an exterior window of a building that was presented in photographs taken at different angles. They found that errors in projective shape judgments were negatively correlated with drawing accuracy (cf. McManus, Loo, Chamberlain, Riley, & Brunswick, 2011). Two other studies using the same (Ostrofsky, Cohen, & Kozbelt, 2014) or similar (Ostrofsky, Kozbelt, & Seidel, 2012) stimuli added a "nondepth" condition (with outline stimuli) to the original "depth" condition. Both studies found greater errors (wider estimates) in the depth compared with the nondepth condition.

No research has directly compared perception of objective and projective shape at different viewing angles with and without context. Such a comparison is critical to test the hypothesis that 3D context can facilitate objective estimates of shape while hindering projective estimates. Here, we used stereo images of 3D surfaces presented with or without 3D context (rather than with or without depth; see Figs. 1a–1c). Previous studies have used either real-world physical stimuli, photographs of real-world stimuli, or computer renderings of real-world stimuli. The advantage of using a binocular stereo paradigm in computer-generated images is that it enhances the percept of three-dimensionality while allowing for precise control of conditions. We hypothesized that objective estimates would be most accurate with the presence of 3D context and projective estimates would be most accurate with the absence of 3D context. Furthermore, accuracy of estimates for the most challenging conditions (objective–no context and projective–context) was predicted to decrease as surface slant increased. Empirical support for these hypotheses would provide strong evidence that 3D context is not only a hindrance for projective shape perception but also a critical component for shape constancy. Findings from this study will establish parameters for the effects of context on judgments of objective and projective shape and identify what visual information within and surrounding a figure is critical for successful shape judgments.

Experiment 1: Effects of Context, Judgment, and Angle on Shape Perception

We first used an alternative-forced-choice paradigm to assess how 3D context affects projective and objective shape judgments of anaglyph images at various degrees of rotation.

Method

Participants. Twelve students (10 female) from the University of Oregon Psychology and Linguistics Departments' Human Subjects Pool participated for course credit. An a priori power analysis (using G*Power Version 3.1; Faul, Erdfelder, Lang, & Buchner, 2007) demonstrated that a sample size of 10 ($\beta = 0.83$ for large effects) was needed to attain sufficient power (0.8 and above) to

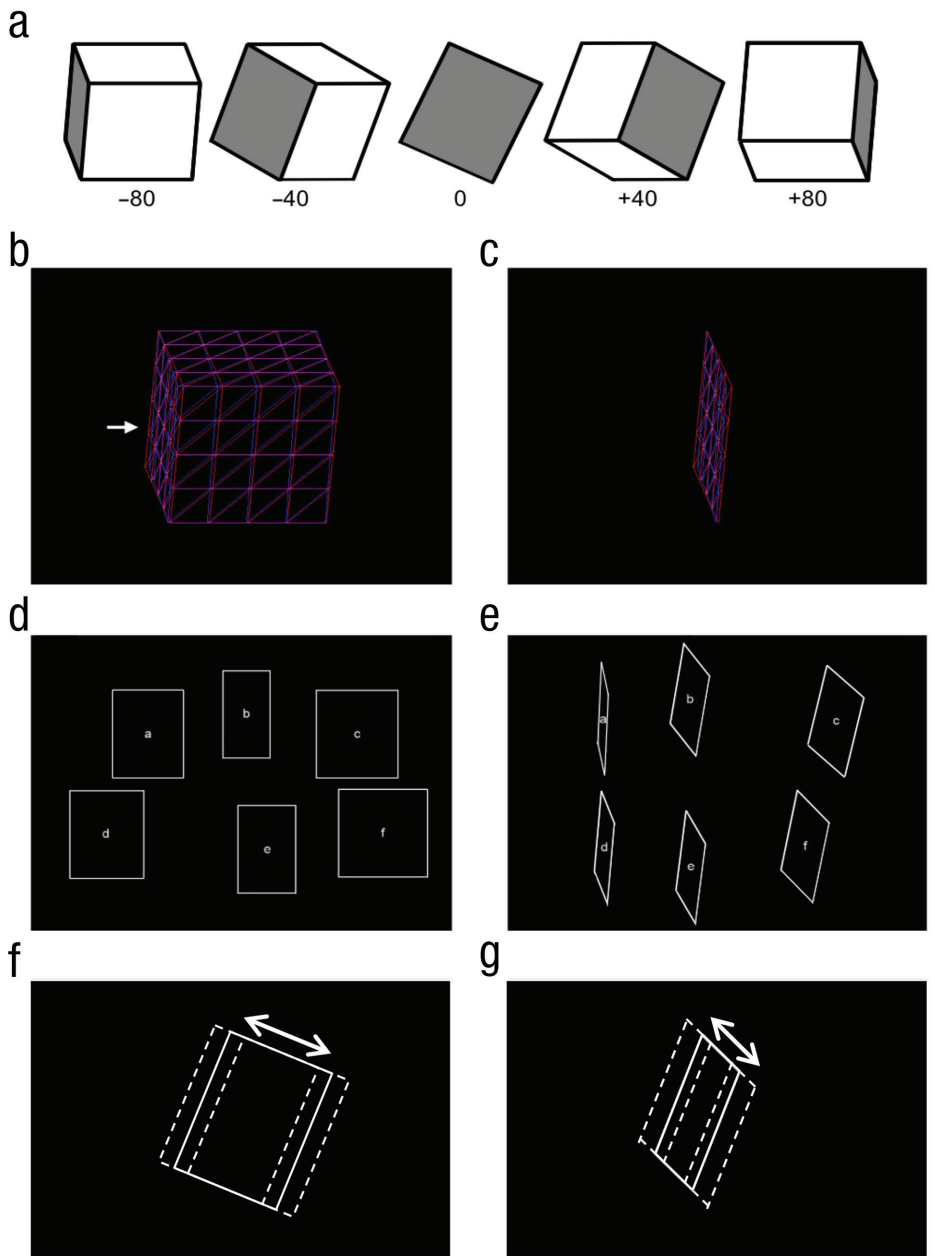

Fig. 1. Example stimuli and response probes for Experiments 1 through 4. Stimuli were polyhedrons rotated in different directions (a); in this schematic, the face of interest is highlighted in gray. Example stimuli used in Experiments 1 and 2 are shown for context-present (context; b) and context-absent (no-context; c) blocks. Participants judged either the rectangle's objective (physical) width, which remained constant at varying angles of rotation, or the rectangle's projective width (the width in the picture plane). Thus, there were four block types consisting of a cross of context (present, absent) and judgment (projective, objective) types. For the context-present conditions, a white arrow (shown in b) indicated the face of interest that should be attended for the subsequent matching judgment. Example alternative-forced-choice response arrays for the matching judgment in Experiment 1 are shown for objective (d) and projective (e) blocks. Participants had to indicate which probe stimulus matched the face of interest and press the appropriate response key, which corresponded to the letter within each option. Example response probes from Experiments 2 through 4 are shown for objective (f) and projective (g) blocks. In these experiments, participants had to adjust the width of the initial response parallelogram to match the previously seen stimulus. The initial response parallelogram was presented as a white outline. Example wider and narrower adjustments are indicated with dashed lines.

detect the expected moderate- to large-sized effects. All participants had normal or corrected-to-normal vision and normal depth perception, as indicated by a score of 8 or above on the Graded Circles Test from the Stereo Fly SO-001 measure of depth perception (Stereo Optical, Chicago, IL). Informed consent was acquired following a protocol approved by the University of Oregon Institutional Review Board.

Stimuli. The stimuli for the experiment consisted of 110 computer-generated red-and-blue anaglyphs presented against a black background at a height of approximately 9° of visual angle. The software to generate the stimuli was written in C (utilizing OpenGL) and Tcl/Tk software (Welch, 2000). The stimuli were systematically rotated polyhedrons drawn with an orthographic projection (see Fig. 1a for a schematic of one polyhedron). The polyhedrons were first rotated downward around the *x*-axis by 25°, then rotated in 10° to 20° increments around the *y*-axis. The orientation of the shapes varied from −80° to +80° from the frontoparallel plane, rotated around the vertical axis, including 11 different possible viewing angles (rotated 0°, ±20°, ±40°, ±60°, ±70°, or ±80°). One half (55) of the stimuli were rectangular cuboid polyhedrons (see Fig. 1b for an example); the other half were isolated rectangles oriented in 3D space (see Fig. 1c for an example). Each rectangle and each visible polyhedral face were completely tessellated with 32 triangles.

Participants judged the width of a rectangle (the face schematically highlighted in gray in Fig. 1a). They judged either the rectangle's objective (physical) width, which remained constant at varying angles of rotation, or its projective width (the width in the picture plane). During blocks that displayed polyhedrons, a small white arrow was used to indicate which of the faces should be attended for a subsequent matching judgment (see Fig. 1b). When facing forward (0° rotation), the depth of the polyhedrons was equal to their height. The width of the polyhedrons varied among five different width-to-height ratios: 0.75, 0.875 (shown in Figs. 1a–1c), 1.0 (square), 1.125, and 1.25. The 110 stimuli, then, consisted of the combination of 11 viewing angles, five object widths, and two shapes (single rectangular face or rectangular face that was part of a polyhedron).

The choice stimuli for the projective-judgment blocks were single face-of-interest stimuli rendered as simple (nonanaglyphic, nontesselated) white outlines. Eighteen different orientations around the vertical axis (one every 5° from 0° to 90°) were rendered for each possible width of the rectangular form. Additional images that were slightly wider than the frontoparallel view of the stimulus were added to the set. A similar procedure was used to generate the choice stimuli for the objective-judgment blocks except that the rectangular forms were rotated to an upright orientation before being rotated around the vertical axis. Figure 1 shows example arrays of objective (see Fig. 1d) and projective (see Fig. 1e) choice stimuli following the presentation of the stimulus shown in Figures 1b or 1c. The individual choice stimuli were presented at the same scale as the face of interest in the stereo stimuli (i.e., not as shown in Figs. 1b–1e).

Procedure and design. Participants sat approximately 21 in. from the computer screen, a standard 19-in. CRT with a screen resolution of 1,024 × 768 pixels. Before testing, they received instructions about the type of stimuli to be presented (single rectangles and rectangular polyhedrons presented at different orientations; see Figs. 1b and 1c) and the type of judgments they were to make (objective and projective). Participants then donned a pair of red-blue anaglyph glasses. Stimuli were then presented stereoscopically in eight blocks of 60 trials for a total of 480 trials.

There were four block types consisting of a cross of context (present vs. absent) and judgment (projective vs. objective) types. There were eight total blocks, two of each kind. Block order was randomized within each set of four blocks. A new block order was presented to each participant. Each block was preceded by descriptors for the upcoming block (e.g., "Context Present / Objective Judgment") and consisted of 5 practice trials followed by one each of the 55 trial types (11 angles × 5 shapes) presented in random order. Between blocks, participants were allowed to rest and could press a button to continue to the next block.

Within a given trial block, participants saw only one type of stimulus, rectangular or polyhedral, and were required to make only one of two possible judgments, projective or objective. In the projective-judgment condition, participants attempted to match the shape in the picture plane of the rectangle or of the indicated face of the polyhedron to one of six possible choices, all of which were parallelograms generated as described in the Stimuli section above. In the objective-judgment condition, participants tried to match the actual shape in 3D space of the rectangle or face to one of six rectangles of varying widths, generated as described above.

An array of six matching stimulus options labeled "a" through "f" were laid out in two rows in random order. Up to five wider- or five narrower-than-correct options were presented. A small amount of random position jitter was introduced into the layouts to reduce the appearance of three-dimensionality that could occur when the choice stimuli were aligned in a perfect grid. Figures 1d and 1e illustrate example objective and projective multialternative choice sets. Participants indicated their choice by pressing one of six buttons labeled with the letters "a" through "f" on an altered computer keyboard consisting of two rows of three letters: "a,"

"b," and "c" were located in the top row and "d," "e," and "f" in the bottom row.

A trial began with the presentation of a stimulus for 1 s followed by 500 ms of a blank screen. Then, the response array was presented until a button was pressed or after 10 s (at which point it was automatically terminated). Within- and between-block randomization, stimulus timing, and response recording were controlled using Presentation software (Neurobehavioral Systems, Albany, CA).

Analysis. To investigate the effects of context, judgment, and rotation angle on perceptual bias, we computed an ordinal-error score (the ordinal position of the chosen response relative to the correct response). Negative scores implied a bias toward narrower-than-actual representations, and positive scores implied a bias toward wider-than-actual representations. A score of 0 would imply no bias, whereas increased absolute value of a score would imply greater perceptual bias. Statistical analyses were carried out in SPSS Version 23.

We predicted that performance would decline as the stimulus was rotated away from a forward-facing orientation (0°). We also predicted that the magnitude of individuals' errors on the objective width-judgment task with context would be smaller than without context. In contrast, we predicted that participants' errors would be greater on the trials with context than those without context when they performed projective width judgments. We also predicted that performance would become worse as the stimulus was angled farther away from 0° but in opposite directions across judgment type. Specifically, we predicted that projective judgments would become wider as rotation increased when 3D context was present, whereas objective judgments would become narrower as rotation increased when context was absent. Thus, we hypothesized that there would be a main effect of judgment: Projective judgments would be wider than objective judgments. We also hypothesized that there would be a main effect of context: Judgments would be wider when context was present than when it was absent. This would be driven by the interactions between angle and context and between angle and judgment—the difference between context and judgment levels should increase as rotation angle increases. These interactions should be similar but opposing, which would not lead to a main effect of angle, an interaction between context and judgment, or an interaction among angle, context, and judgment.

Results

Data were analyzed using a 2 × 2 × 6 analysis of variance (ANOVA) with context (present, absent), judgment (objective, projective), and rotation angle (0°, 20°, 40°, 60°, 70°, 80°) as within-subjects factors.

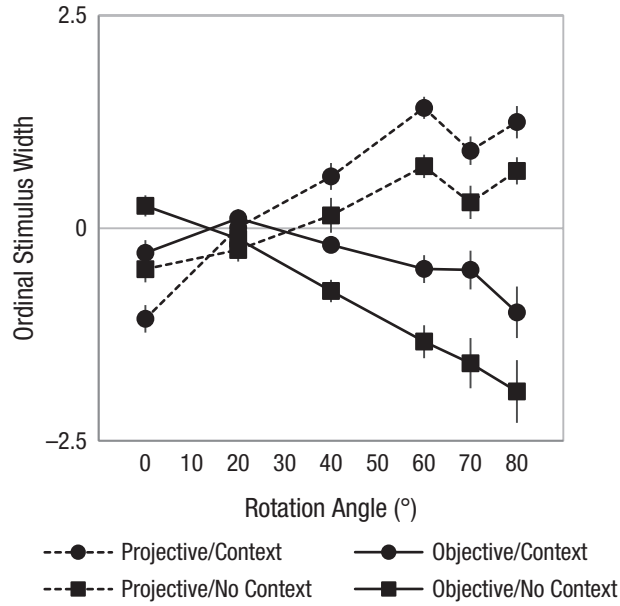

Fig. 2. Results of Experiment 1 (alternative-forced-choice method). Response bias, as measured by ordinal stimulus width (ordinal position of the chosen response relative to the correct response), is plotted as a function of stimulus rotation angle (0°, 20°, 40°, 60°, 70°, 80°), context (context, no context), and judgment type (projective, objective). Error bars represent ±1 *SEM*. On the *y*-axis, values above 0 are wider estimates of width, and values below 0 are narrower estimates of width.

Mauchly's test indicated that the assumption of sphericity was violated for rotation angle, $\chi^2(14) = 47.20$, $p < .001$; the Judgment × Angle interaction, $\chi^2(14) = 51.93$, $p < .001$; and the Context × Judgment × Angle interaction, $\chi^2(14) = 25.98$, $p = .03$, but not for the Context × Angle interaction, $\chi^2(14) = 22.36$, $p < .08$. Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .296$, .289, and .616).

There were main effects of context, $F(1, 11) = 35.486$, $p < .001$, $\eta^2 = .763$; judgment, $F(1, 11) = 44.392$, $p < .001$, $\eta^2 = .801$; and (weakly) rotation angle, $F(5, 55) = 4.063$, $p < .047$, $\eta^2 = .270$. These were qualified by interactions between angle and context, $F(5, 55) = 26.622$, $p < .001$, $\eta^2 = .708$, as well as angle and judgment, $F(1.443, 15.875) = 50.255$, $p < .001$, $\eta^2 = .820$ (see Fig. 2). There were no significant interactions between context and judgment, $F(1, 11) = 0.843$, $p = .38$, $\eta^2 = .071$, or among angle, context, and judgment, $F(3.082, 33.904) = 0.970$, $p = .42$, $\eta^2 = .081$. These findings were consistent with our hypotheses and suggest that the presence of context interferes with performance in projective judgments, whereas objective judgments are impaired when context is lacking. Further, these effects occur across varying degrees of rotation.

Discussion

Our results show that shape estimates using anaglyph stimuli vary as a function of judgment, context, and angle. Specifically, 3D context aids objective judgments but hinders projective judgments, whereas a lack of context aids projective judgments and hinders objective judgments.

Experiment 2: Replication Using a Method-of-Adjustment (MOA) Approach

To obtain more refined estimates of shape perception, we asked participants in a second experiment to complete a task with the same design but used an MOA approach to collect participant responses.

Method

Participants. Eighteen students (12 female) from the University of Oregon Psychology and Linguistics Departments' Human Subjects Pool participated for course credit. An a priori power analysis (using G*Power Version 3.1) demonstrated that a sample size of 18 ($\beta = 0.82$ for moderate effects) was needed to attain sufficient power (0.8 and above) to detect the expected moderate- to large-sized effects. As before, all participants had normal or corrected-to-normal vision and normal depth perception, as indicated by a score of 8 or above on the Graded Circles Test.

Stimuli. The to-be-remembered stimuli were the same as those used in Experiment 1, but the response stimulus changed. The adjustable test shape was a correct rendering of the face-of-interest stimulus (narrow, medium, or wide width) as a simple white outline, with its width offset by a random amount (−45 to +45 pixels; see Figs. 1f and 1g). For the projective-judgment blocks, the test shape was an outline of the projective image (the shape in the picture plane) of the rotated face of interest with width jitter added to the rotated face. For the objective-judgment blocks, it was the physically correct shape of the target surface, again with jitter added to the width.

To directly compare objective and projective shape estimates, we had participants make adjustments to the actual physical width of the face of interest. Therefore, when participants adjusted the objective probe, they changed the width of the face of interest (which is shown facing forward in the frontoparallel plane) to match their perception of the objective width of the rotated face of interest. Likewise, when participants adjusted the projective probe to match their perception of the projective width, they were adjusting the actual width of the rotated face of interest, which was presented and perceived as a projective outline. We used this adjustment method because (a) it allowed for a direct comparison between the two types of judgments using a common baseline (the physical width of the face of interest), (b) it required participants to make adjustments to the actual width of the face of interest in both conditions (one face forward facing and the other rotated), and (c) we could collapse the data across the polyhedrons of differing widths, which would allow us to measure error straightforwardly in the same way as an offset from a given width.

Procedure and design. The procedure and design were similar to that described in Experiment 1 with a few exceptions. Here, there were 16 blocks, 4 of each kind, and each block consisted of 54 trials comprising two repetitions of each of the 27 stimuli (9 angles × 3 shapes). Text indicating block and judgment type (e.g., "Context Present / Objective Judgment") was followed immediately by experimental trials—no practice was included in Experiment 2.

A trial began with the presentation of a stimulus for 3 s followed by 1 s of a blank screen. After that, the response parallelogram was displayed, and participants changed its width using the up (wider widths) and down (narrower widths) arrow keys. When participants were finished, they pressed the space bar, at which point the response parallelogram disappeared. The next trial began after a 1-s delay. Trials were randomized within blocks, and blocks were randomized within the experiment. Within- and between-block randomization, stimulus timing, and response recording were controlled using MATLAB (The MathWorks, Natick, MA) and the Psychophysics Toolbox (Brainard, 1997).

Analysis. We measured error bias (i.e., the directionality and magnitude of error) by calculating the difference between reported width and correct physical width on each trial (wider-than-correct responses resulted in positive values; narrower-than-correct responses resulted in negative values). Error bias was recorded in pixels but is reported here as degrees of visual angle. Scores were computed for each trial and averaged within conditions (collapsed across positive/negative rotation at each rotation angle and across all object widths) for each participant. Our predictions were the same as for Experiment 1. We predicted that performance would decline as the stimulus was rotated away from a forward-facing orientation. Regarding overall performance, we predicted that individuals would perform better at the objective width-judgment task with context than without context and that performance would suffer on the trials with context compared with the trials without context when they performed projective width judgments. We also predicted that performance would become worse as the stimulus was angled farther away from 0° but in opposite

directions across judgment and context type. Because both judgments were compared with the actual width of the face of interest, perfect objective and projective width estimates correspond to zero error, wider estimates to positive error values, and narrower estimates to negative error values. Our specific predictions regarding rotation angle were that projective judgments would become wider (positive error values) as rotation increased when 3D context was present, whereas objective judgments would become narrower (negative error values) as rotation increased when context was absent. Also, as rotation angle increased, conditions with context would produce wider judgments and those without context would produce narrower judgments.

Thus, we hypothesized that there would be a main effect of judgment: Projective judgments would be wider than objective judgments. We also hypothesized that there would be a main effect of context: Judgments should be wider when context was present than when it was absent. This would be driven by the interactions between angle and context and between angle and judgment. These should be similar but opposing effects of angle that would not lead to a main effect of angle, an interaction between context and judgment, or an interaction among angle, context, and judgment.

We corrected for a small size-constancy confound in the data. The probe stimulus was presented at 0° disparity, whereas the mean depth of the face of interest was in front of the 0° disparity plane. In addition, the least rotated stimuli were at a farther distance from the 0° disparity plane than the most rotated stimuli. Because of size-constancy mechanisms, estimates of width were expected to be narrower for all of the angles of rotation but with the greatest effects on the least rotated stimuli. This was confirmed by the results in Experiments 1 and 2. Error bias, collapsed over all conditions, was on average negative in both experiments (−0.2 ordinal stimulus width in Experiment 1 and −0.03° of visual angle in Experiment 2). Error bias was also more negative for the smallest (20° and 40°) compared with the largest (60° and 80°) rotations. To correct for this small artifact, we subtracted the net bias for each angle (i.e., the mean error bias) from the individual bias scores for that angle (similar to calculating a z score except without dividing by the standard deviation). The adjusted bias scores were then used to compute error bias. The results reported below were similar with or without the size-constancy correction.

Results

Data were first cleaned by removing trials in which response times were extremely short (< 500 ms) or long (> 30 s; 4.4% of trials discarded). Data were then analyzed using a 2 × 2 × 5 ANOVA with context (present, absent), judgment (objective, projective), and rotation angle (0°, 20°, 40°, 60°, 80°) as within-subjects factors. Mauchly's test indicated that the assumption of sphericity had been violated for rotation angle, $\chi^2(9) = 44.468$, $p < .001$; the Judgment × Angle interaction, $\chi^2(9) = 70.091$, $p < .001$; and the Context × Judgment × Angle interaction, $\chi^2(9) = 18.360$, $p = .032$, but not the Context × Angle interaction, $\chi^2(9) = 13.242$, $p = .154$. Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .410$, .321, and .682, respectively).

There were main effects of context, $F(1, 17) = 48.838$, $p < .001$, $\eta^2 = .742$, and judgment, $F(1, 17) = 4.424$, $p = .051$, $\eta^2 = .207$ (see Fig. 3a). These were mediated by interactions between context and angle, $F(4, 68) = 24.173$, $p < .001$, $\eta^2 = .587$ (Fig. 3b), and judgment and angle, $F(1.284, 21.832) = 21.079$, $p < .001$, $\eta^2 = .554$ (Fig. 3c). There was no interaction between context and judgment, $F(1, 17) = 0.822$, $p = .377$, $\eta^2 = .046$, or among angle, context, and judgment, $F(2.727, 46.365) = 1.484$, $p = .233$, $\eta^2 = .080$. These effects are consistent with those observed in Experiment 1 and the predictions of the influence of context, judgment type, and angle of rotation of width judgments.

Discussion

We conceptually replicated the effects from the first experiment using a more sensitive response measure. Performance decreased as the stimulus was angled away from 0° but in opposite directions across context and judgment type. Specifically, width estimates became wider as rotation increased when context was present and became narrower when context was absent (Fig. 3b). Also, projective judgments became wider and objective judgments became narrower as rotation increased (Fig. 3c). Interestingly, there are some slight nonzero error biases for the 0°-visual-angle condition in Experiments 1 and 2 (see Figs. 2 and 3). This can be seen most clearly for Experiment 2 in Figure 3c, which shows a slightly positive (wider) estimate for the objective compared with a slightly negative (narrower) estimate for the projective judgments even though all matches were made to the same stimulus shape (the face of interest facing forward). A possible explanation is that participants were slightly biased to make wider objective judgments and narrower projective judgments because across conditions, objective shapes were always the same or wider than projective shapes.

Experiment 3: Effects of Partial Context

In Experiment 3, we examined the extent to which manipulating context by varying the width of the non-judged contextual faces was needed to produce strong contextual effects on shape perception.

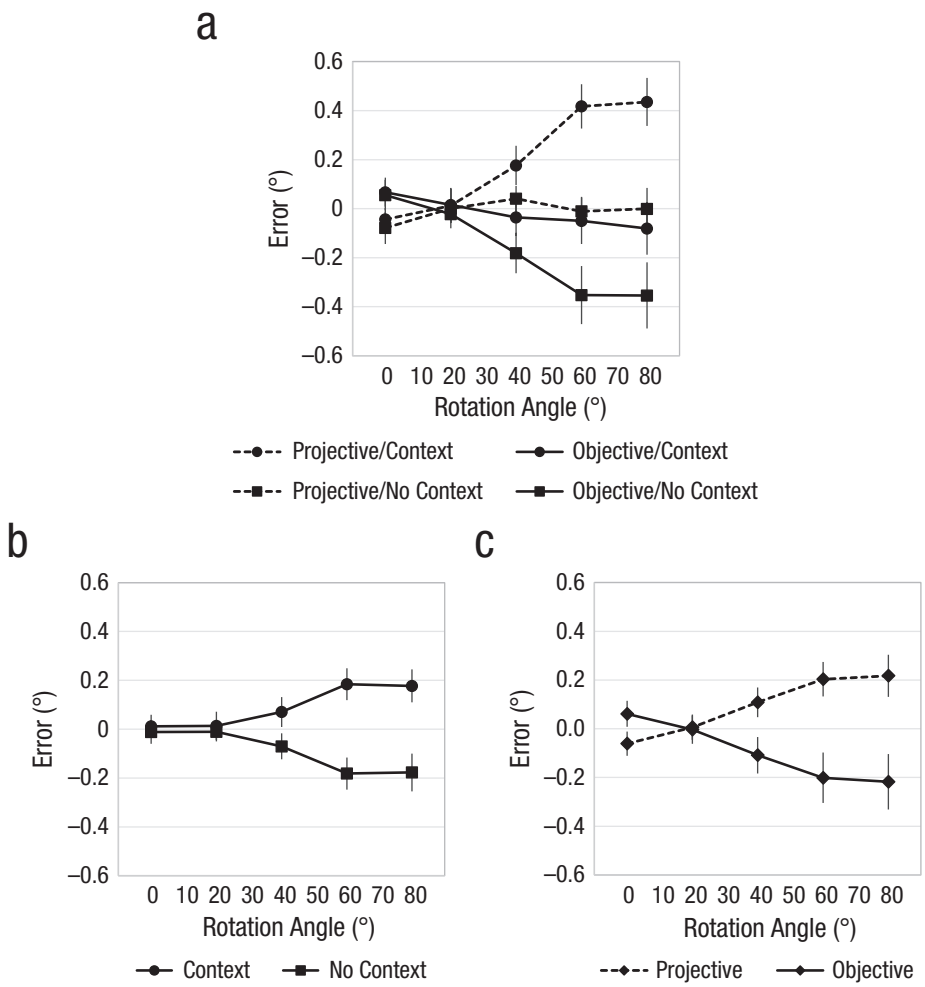

Fig. 3. Results of Experiment 2 (method-of-adjustment approach). Error bias, as measured by the difference between reported and correct width, is plotted as a function of stimulus rotation angle (0°, 20°, 40°, 60°, 80°) and (a) context (context, no context) and judgment type (projective, objective), (b) context only, and (c) judgment type only. On the *y*-axis, values above 0 are wider estimates of width, and values below 0 are narrower estimates of width. Error bars represent ±1 *SEM*.

Method

Participants. Thirty-two students (18 female) from the University of Oregon Psychology and Linguistics Departments' Human Subjects Pool participated for course credit. An a priori power analysis (using G*Power Version 3.1) demonstrated that a sample size of 19 ($\beta = 0.81$ for moderate effects) was needed to attain sufficient power (0.8 and above) to detect the expected moderate- to large-sized effects. A larger sample size than the minimum suggested by the power analysis was used to better approximate normal distributions in the data. As before, all participants had normal or corrected-to-normal vision and normal depth perception, as indicated by a score of 8 or above on the Graded Circles Test.

Stimuli. The to-be-remembered stimuli were similar to those used in Experiment 2, but in addition to the context-absent (no context) and context-full (full context) stimuli, a 3D figure with partial context was included (see Fig. 4a). The polyhedral stimuli with partial context (Fig. 4a, middle image) contained 25% of the context compared with the full-context stimuli (Fig. 4a, right image). The adjustable test stimuli remained the same as in Experiment 2 but with random width offset of −30 to +30 pixels.

Procedure and design. Participants sat approximately 15 in. from the computer screen, a 24-in. LED backlit monitor with a resolution of 1,920 × 1,080 pixels. The procedure and design for the current experiment were similar to that of the second experiment but included an additional intermediate level of context. Here, there were six blocks, two of each kind of context condition, and each block consisted of 36 trials comprising two repetitions of each of the 18 stimuli (6 angles × 3 shapes). Text indicating block and judgment type (e.g., "Context Present / Objective Judgment") was presented immediately before experimental trials, and we had participants complete six

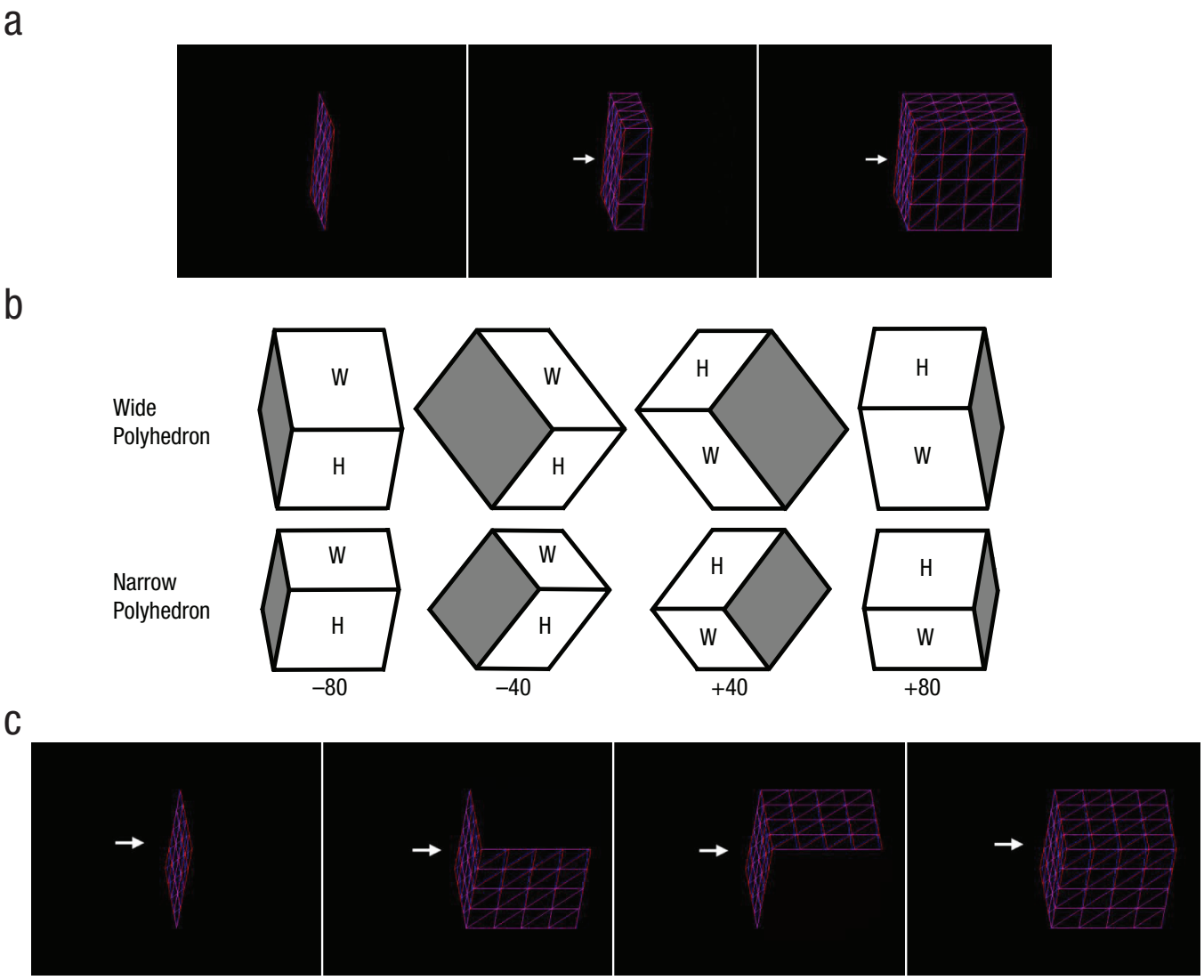

Fig. 4. Stimuli used in Experiments 3 and 4. The three types of stimuli in Experiment 3 (a) had no context (left), partial context (middle), or full context (right). The partial-context stimulus contained 25% of the contextual information present in the full-context stimulus. The schematic representation (b) shows four rotation angles of the polyhedral stimulus sets in Experiment 4. The widest set is shown in the top row, and the narrowest set is shown in the bottom row. The face of interest is highlighted in gray. In contrast to the stimuli in Experiments 1 through 3, the polyhedrons in Experiment 4 were first rotated downward around the *x*-axis by 45° (rather than 25°), then rotated around the *y*-axis as before so that both contextual faces were equally visible across the stimulus set. The rotation angle specifies the amount of rotation (±°) from the frontoparallel plane. The "H" label refers to the contextual plane that borders the height dimension of the face of interest, and the "W" refers to the contextual plane that borders the width dimension of the face of interest. Panel (c) displays all conditions (ranging from no context on the left to full context on the right) of the narrowest polyhedral stimulus with a –80° rotation. The two center images depict incomplete three-dimensional polyhedral figures with a single contextual plane containing information about the height of the face of interest (second from the left) or the width of the face of interest (third from the left). The white arrows in (a) and (c) indicate the face of interest that participants were asked to attend.

practice trials before the experimental trials to ensure they understood the task.

As in the previous experiments, trials began with the presentation of a stimulus for 3 s, followed by a blank screen for 1 s. Then the response parallelogram was displayed, and participants adjusted it in width using the up (wider widths) and down (narrower widths) arrow keys. Participants pressed the space bar when they were finished, at which point the response parallelogram disappeared, and the next trial began after a 1-s delay. All trials were randomized within blocks. The two repetitions of the six blocks were presented in sequence; block order was randomized within each sequence. Within- and between-block randomization, stimulus timing, and response recording were controlled using MATLAB and the Psychophysics Toolbox.

Analysis. As in Experiment 2, we measured the error bias for each trial and adjusted scores to account for the size-constancy artifact. Error bias was recorded in pixels

and then converted to degrees of visual angle. We predicted that we would observe a main effect of context on shape judgments, with no-context conditions leading to narrower width estimates and any level of context (partial or full) leading to wider width judgments. We also predicted a main effect of judgment, with projective width estimates being narrower than correct width estimates and objective width estimates being wider than correct width estimates, as well as a Judgment × Angle interaction—as angle increases, projective judgments should become wider and objective judgments narrower.

Results

Data were first cleaned by removing trials in which response times were extremely short (< 500 ms) or long (> 30 s; 1.3% of trials were discarded). Data were then analyzed using a 3 × 2 × 3 ANOVA with context (present, partial, absent), judgment (objective, projective), and rotation angle (40°, 60°, 80°) as within-subjects factors. Mauchly's test indicated that the assumption of sphericity had been violated for rotation angle, $\chi^2(2) = 9.445$, $p = .009$; the Judgment × Angle interaction, $\chi^2(2) = 11.317$, $p = .003$; and the Context × Judgment × Angle interaction, $\chi^2(9) = 19.817$, $p = .019$, but not for context, $\chi^2(2) = 5.228$, $p = .073$; the Context × Judgment interaction, $\chi^2(2) = 2.606$, $p = .272$; and the Context × Angle interaction, $\chi^2(9) = 14.311$, $p = .112$. Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .787$, .761, and .747, respectively).

There were main effects of context, $F(2, 62) = 28.496$, $p < .001$, $\eta^2 = .479$, and judgment, $F(1, 31) = 37.934$, $p < .001$, $\eta^2 = .550$ (see Figs. 5a and 5b). The main effect of judgment was mediated by a Judgment × Angle interaction, $F(1.522, 47.176) = 13.609$, $p < .001$, $\eta^2 = .305$ (see Fig. 5c). There was no main effect of angle, $F(1.575, 48.815) = 0.005$, $p = .987$, $\eta^2 = .000$; no interactions between context and judgment, $F(2, 62) = 0.363$, $p = .697$, $\eta^2 = .012$, or context and angle, $F(4, 124) = 0.267$, $p = .899$, $\eta^2 = .009$; and no interaction among angle, context, and judgment, $F(2.990, 92.676) = 0.166$, $p = .919$, $\eta^2 = .005$. These effects were consistent with those observed in Experiments 1 and 2. The Judgment × Angle interaction (Fig. 5c) was similar to that found in Experiments 1 and 2. As predicted, as angle increased, projective judgments became wider and objective judgments narrower. In addition, the main effect of context indicated that error bias was different across levels of context (Fig. 5b). When participants made width judgments with stimulus context (partial or full), error bias was positive (wider judgments) for partial context and for full context. In contrast, when they made judgments with no context, error bias was negative (narrower judgments). Importantly, even a small amount of context (25% of full context) situated next to the face of interest produced effects similar to those in the full-context condition.

Discussion

The results demonstrated that both context conditions (full and partial, which is 25% of full context) had similar effects on width judgments. Thus, even a small amount of surrounding context had a strong influence on shape judgments.

Experiment 4: Effects of Incomplete Context

In Experiment 4, we varied context by eliminating one of the two faces that border the face of interest to evaluate the contribution of each face to the shape judgments (see Figs. 4b and 4c). Each contextual face may contribute information about the width of the face of interest in one of two ways. The "width" contextual plane (labeled "W" in Fig. 4b) may contribute information by providing an independent estimate of the width. In contrast, the "height" contextual plane (labeled "H" in Fig. 4b) may contribute information by providing an estimate of slant that is linked to the slant of the face of interest because it is in a fixed (perpendicular) relationship to the face of interest. According to the shape-slant-invariance hypothesis, a better estimate of surface slant should lead to better estimates of shape (i.e., width).

Method

Participants. Thirty-four students (27 female) from the University of Oregon Psychology and Linguistics Departments' Human Subjects Pool participated for course credit. An a priori power analysis (using G*Power Version 3.1) demonstrated that a sample size of 16 ($\beta = 0.81$ for moderate effects) was needed to attain sufficient power (0.8 and above) to detect the expected moderate- to large-sized effects. A larger sample size than the minimum suggested by the power analysis was used to better approximate normal distributions in the data. All participants had normal or corrected-to-normal vision and normal depth perception, as indicated by a score of 8 or above on the Graded Circles Test.

Stimuli. The to-be-remembered stimuli were similar to those used in Experiment 2, but in addition to the context-absent and context-full stimuli, two additional sets of stimuli, each lacking one of the two contextual polyhedral faces, were included (see Fig. 4c). Stimuli containing information about the height of the face of interest (e.g., Fig. 4c) were 3D shapes missing the "width" contextual plane

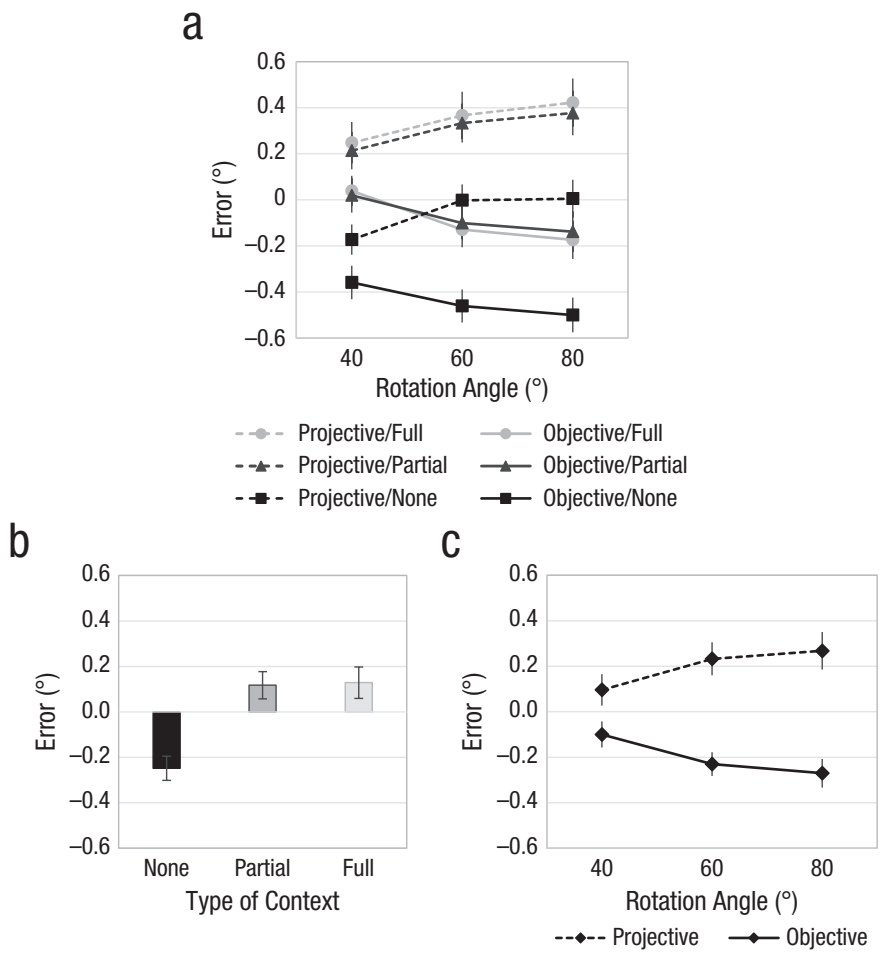

Fig. 5. Results of Experiment 3 (method-of-adjustment approach). Error bias, as measured by the difference between reported and correct width, is plotted as a function of stimulus rotation angle (40°, 60°, 80°) and (a) context (full, partial, or none) and judgment type (projective, objective), (b) context only, and (c) judgment type only. On the *y*-axis, values above 0 are wider estimates of width, and values below 0 are narrower estimates of width. Error bars represent ±1 *SEM*.

of the polyhedron. Stimuli containing information about the width of the face of interest (e.g., Fig. 4c) were 3D shapes missing the "height" contextual plane of the polyhedron. Response stimuli were similar to those used in Experiment 3 (with random width offset of −30 to +30 pixels). In contrast to the stimuli in Experiments 1 through 3, the polyhedrons in the current experiment were first rotated downward around the *x*-axis by 45° (rather than 25°), then rotated in 20° increments around the *y*-axis. This was done so that both contextual faces were equally visible. The orientation of the shapes varied from −80° to +80° from the frontoparallel plane, rotated around the vertical axis, including six different possible viewing angles (rotated ±40°, ±60°, or ±80°; see Fig. 4b for a schematic of wide and narrow polyhedrons rotated ±40° and ±80°).

Procedure and design. The procedure and design were similar to those in Experiment 3. Participants made two types of judgments either in the presence or in the absence of additional context. In Experiment 4, there were eight blocks, two of each kind of context condition. Each block consisted of 36 trials comprising two repetitions of each of the 18 stimuli (6 angles × 3 shapes). Text indicating block and judgment type (e.g., "Context Present / Objective Judgment") was presented immediately before experimental trials, and 8 practice trials were completed before experimental trials to ensure understanding of the task.

Trials began with the presentation of a stimulus for 3 s followed by a blank screen for 1 s. After that, the response parallelogram was displayed, and the participant adjusted its width using the up (to increase width) and down (to decrease width) arrow keys. When participants were finished, they pressed the space bar, at which point the response parallelogram disappeared, and the next trial began after a 1-s delay. All trials were randomized within

blocks. The two repetitions of the eight blocks were presented in sequence; block order was randomized within each sequence. Within- and between-block randomization, stimulus timing, and response recording were controlled using MATLAB and the Psychophysics Toolbox.

Analysis. We measured the magnitude of bias (a signed measure of deviation from the correct width) for each trial. Error bias was recorded in pixels and converted to degrees of visual angle. We hypothesized that there would be a main effect of judgment, with projective judgments being wider than objective judgments. We also hypothesized that there would be a main effect of context, with judgments being wider when context was full or incomplete compared with when it was absent. Additionally, we predicted a Judgment × Angle interaction—as angle increased, projective judgments should become wider and objective judgments narrower—and possibly a Context × Judgment interaction—the range of context (none, incomplete, full) should have opposite effects on objective and projective judgments. We hypothesized that the single (incomplete) contextual surfaces could influence width estimates in one of two ways. First, the bordering faces may provide independent estimates of the face of interest's height or width. If this is the case, then we predicted that the condition with width context should produce estimates of width similar to the condition with the full context. Alternatively, if the contextual planes improve estimates of apparent slant, then the condition with height context should produce estimates of width similar to the condition with full context.

Results

Data were first cleaned by removing trials in which response times were extremely short (< 500 ms) or long (> 30 s; 0.6% of trials were discarded). Data were then analyzed using a 4 × 2 × 3 ANOVA with context (present, partial-height, partial-width, absent), judgment (objective, projective), and rotation angle (40°, 60°, 80°) as within-subjects factors. Mauchly's test indicated that the assumption of sphericity had been violated for rotation angle, $\chi^2(2) = 9.148$, $p = .010$, and the Judgment × Angle interaction, $\chi^2(2) = 16.016$, $p < .001$, but not for context, $\chi^2(5) = 5.414$, $p = .368$; the Context × Judgment interaction, $\chi^2(5) = 2.326$, $p = .803$; the Context × Angle interaction, $\chi^2(20) = 30.789$, $p = .059$; and the Context × Judgment × Angle interaction, $\chi^2(20) = 21.629$, $p = .364$. Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .801$ and .717, respectively).

There were main effects of context, $F(3, 99) = 14.517$, $p < .001$, $\eta^2 = .306$, and judgment, $F(1, 33) = 6.562$, $p = .015$, $\eta^2 = .166$ (see Fig. 6a). These main effects were mediated by a Context × Judgment interaction, $F(3, 99) = 3.543$, $p = .017$, $\eta^2 = .097$ (see Fig. 6b) and a Judgment × Angle interaction, $F(1.435, 47.353) = 18.988$, $p < .001$, $\eta^2 = .365$ (see Fig. 6c). There was no main effect of angle, $F(1.602, 52.857) = 0.006$, $p = .986$, $\eta^2 = .000$; no interaction between context and angle, $F(6, 198) = 0.776$, $p = .590$, $\eta^2 = .023$; and no interaction among angle, context, and judgment, $F(6, 198) = 0.890$, $p = .503$, $\eta^2 = .026$.

These effects were consistent with those observed in Experiments 1 through 3. The Judgment × Angle interaction (Fig. 6c) was similar to that found in Experiments 1 through 3. As predicted, as angle increased, projective judgments became wider and objective judgments narrower. The Context × Judgment interaction indicated that the range of context (none, incomplete, full) had opposite effects on objective and projective judgments. As participants went from no to full context, projective error increased (from low error bias to wider estimates of width) and objective error decreased (from narrow estimates of width to low error bias; see Fig. 6b). As shown in Experiments 1 through 3, full context made objective judgments more accurate and projective judgments less accurate (wider). Also as shown in Experiments 1 through 3, no context made projective judgments more accurate and objective judgments less accurate (narrower). Effects of height context were more similar to those of full context, whereas the effects of width context were more similar to those of no context.

Discussion

The two incomplete-context conditions did not have equivalent effects on width judgments. The effects of height context were similar to the effects of full context, and the effects of width context were similar to the effects of no context (see Fig. 6b). The fact that the effects of width context were similar to the effects of no context suggests that the independent estimate of width that width context may provide does not contribute substantially to the width estimate of the face of interest. Instead, these results support the shape-slant-invariance hypothesis, which suggests that perception of objective shape is determined by combining estimates of projective shape and apparent slant (Epstein, 1973; Massaro, 1973). In our case, height context had similar effects to full context because it helped participants determine the slant of the face of interest linked to the width judgment. That is, because the height contextual plane was in a fixed perpendicular relationship with the face of interest, slant information extracted from this plane might have improved the estimate of the slant of the surface of interest in a direction that was helpful to obtaining an accurate width (rather than height) estimate.

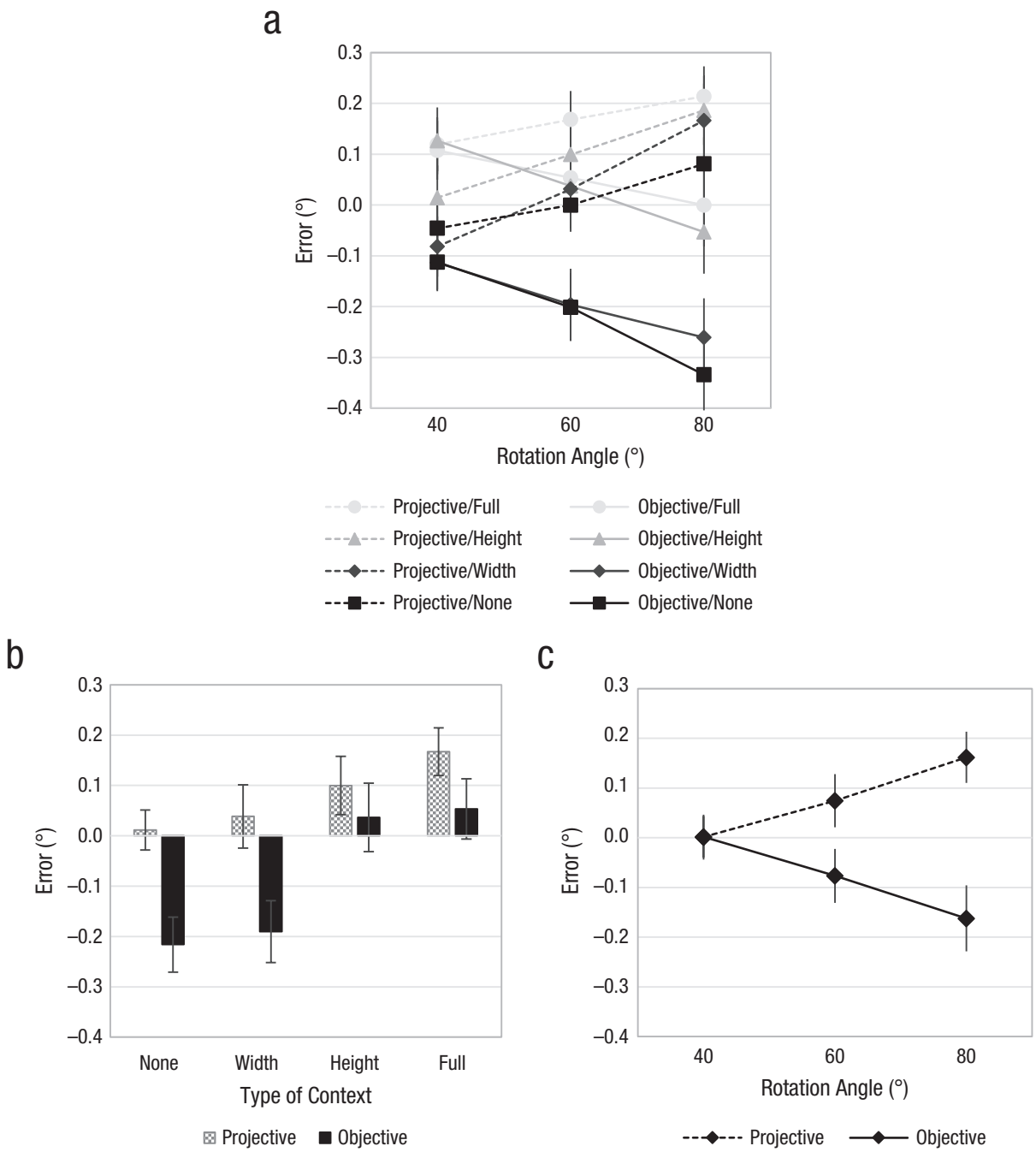

Fig. 6. Results of Experiment 4 (method-of-adjustment approach). Error bias, as measured by the difference between reported and correct width, is plotted as a function of stimulus rotation angle (40°, 60°, 80°) and (a) context (none, width, height, full) and judgment type (projective, objective), (b) context only, and (c) judgment type only. On the *y*-axis, values above 0 are wider estimates of width, and values below 0 are narrower estimates of width. Error bars represent ±1 *SEM*.

Discussion

Our four experiments demonstrated robust effects of 3D context on shape perception. We rendered quadrilateral surfaces of varying widths as skeletal outlines embedded in a cuboid polyhedron or as an isolated shape, rotated around the viewing plane, and presented as anaglyphs. In a fully crossed design, we investigated how the variables of context, instruction (projective or objective judgments), and angle interacted. Overall, we found that 3D context aids objective judgments but hinders projective judgments, whereas a lack of context

aids projective judgments and hinders objective judgments. Specifically, errors were centered around the correct response when instruction and context were consistent ("Objective/Context" and "Projective/No Context"). In contrast, errors became increasingly biased toward the context-influenced width estimate as rotation increased when instruction and context were inconsistent (narrower for "Objective/No Context" and wider for "Projective/Context"). This suggests that perception becomes anchored on the narrower projective shape in the absence of context and on the wider objective shape in the presence of context.

These results show definitively what has been reported in a piecemeal fashion in the literature but not directly tested—that context facilitates objective judgments (Lappin & Preble, 1975; Olsen et al., 1976) but impedes projective judgments (Mitchell et al., 2005; Ostrofsky et al., 2014; Ostrofsky et al., 2012) and that a lack of context impedes objective judgments (e.g., Massaro, 1973). Regarding projective judgments without context, Thouless (1931a, 1931b) and others have reported a shift in judgment in the direction of the objective shape, whereas our results showed only a small shift in that direction (see Figs. 2, 3a, 5a, and 6a) compared with the projective-with-context condition.

Our results also demonstrated that the presence of even a small amount of context bordering the face of interest produced context effects similar to those in the full-context condition (Experiment 3). In applied terms, this would be similar to a thin rectangular cuboid such as a book providing similar shape cues as a tissue box. In addition, providing incomplete context (by presenting only one of the two faces that border the face of interest) showed that the presence of the height contextual plane (the plane bordering the height dimension of the face of interest) produced context effects similar to those in the full-context condition (Experiment 4). This supports the shape-slant-invariance hypothesis in that height context appears to improve the estimate of the slant of the face of interest that is linked to the width (rather than height) judgment. More generally, it suggests that the presence of contextual surfaces of different orientations facilitates shape constancy. Pizlo and colleagues (e.g., Pizlo, 2008; Pizlo, Sawada, Li, Kropatsch, & Steinman, 2010) discuss some of the pitfalls of studying 3D shape perception with simple geometric stimuli under reduced viewing conditions and demonstrated that the 3D shape of volumetric multiplanar contour stimuli can be recovered by humans and machines. Our results are consistent with this work in demonstrating that context, in the form of multiple connected planar surfaces forming a volumetric or partially volumetric shape, improves the objective shape estimate of an embedded planar surface.

Finally, our experimental paradigm will be useful in testing theories regarding the relationship between perception and drawing skill. Skill in drawing relies on the perceptual ability to render projective shape irrespective of context. This can be accomplished if the perceiver has a local processing bias (i.e., enhanced local processing at the expense of global processing) or a flexible processing style in which context can be ignored (e.g., when drawing) or utilized (e.g., for shape constancy) as needed. Most research has focused on testing local processing abilities and biases (e.g., Drake & Winner, 2011), including the ability to make projective shape judgments with context (e.g., Cohen & Jones, 2008). However, other research suggests that global processing is not impaired in participants with drawing skill (Chamberlain, McManus, Riley, Rankin, & Brunswick, 2013). To tease these theories apart, future research must test context effects on shape perception comprehensively as we have done here. In conclusion, we have developed a shape-perception task that broadly tests the effects of context on shape perception, will prove useful for future investigations of individual differences in perceptual processing, and can be applied to studies of drawing skill.

Transparency

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Author Contributions
All of the authors contributed to the study design. M. E. Sereno, A. J. Bies, and K. E. Robles contributed to stimulus generation; A. Kikumoto, M. E. Sereno, and A. J. Bies programmed the experiments; K. E. Robles, A. Kikumoto, and A. J. Bies performed testing and data collection; and M. E. Sereno, A. J. Bies, and K. E. Robles analyzed and interpreted the data. M. E. Sereno, A. J. Bies, and K. E. Robles drafted the manuscript. All of the authors edited the manuscript and approved the final version for submission.
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The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.
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Open Practices
All data and materials have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/72q3w/ and https://osf.io/5m6dj/, respectively. The design and analysis plans for the experiments were not preregistered. The complete Open Practices Disclosure for this article can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797620901749. This

article has received the badges for Open Data and Open Materials. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.

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