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The nature of shape constancy mechanisms as revealed by shape priming

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Five shape priming experiments are reported in which the target was either a five- or six-sided line-drawn figure and participants made a speeded two-alternative forced-choice judgment about the target's number of sides. On priming trials, the target was preceded by a briefly presented smaller line figure (the prime) and performance on these trials was gauged relative to a no-prime condition. In the first two experiments, primes were rendered invisible by the presentation of a backwards visual noise mask, respectively for a short (~40 ms) or long duration (~93 ms). No reliable priming effects arose under masked conditions. When these experiments were repeated without the mask, participants were speeded when the prime and target were related by a rigid through-the-plane rotation but not when the prime was a nonrigid, stretched version of the target. The same pattern of priming effects arose when, in a final experiment, novel irregular shapes were used. Collectively, the data reveal the operation of shape constancy mechanisms that are particularly sensitive to shape rigidity. The findings suggest that the visual system attempts to secure a correspondence between the rapid and successive presentations of the prime and the target by matching shapes according to a rigidity constraint.

Introduction

The present series of experiments arose through consideration of a recent paper by Norman, Akins, Heywood, and Kentridge (2014). In a series of metacontrast masking experiments, they found that color constancy can be achieved unconsciously and with extraordinary speed. The central question we address here is whether the same is true of shape constancy. This question is of some importance because the extant data suggest that shape constancy appears to operate in ways that are different from those that Norman et al. (2014) found for color constancy.

In the experiments reported by Norman et al. (2014), subjects were presented with a sequence of displays, the background of which consisted of square matrix in which each cell was a colored square. In all of the displays, the matrix was divided according to the negative diagonal, so that the lower left cells of the matrix and the upper right cells appeared to be illuminated differently: One half of the matrix was rendered as to resemble illumination by direct sunlight and the other was rendered as to resemble illumination by average sunlight. On the majority of trials, a small colored disc, the prime, briefly occurred at a cued location superimposed on the matrix. Across trials the luminance of the respective background regions switched randomly but the prime was always situated in the portion of the matrix illuminated as if in direct sunlight. After the prime was extinguished, the luminance boundary then shifted either upwards or downwards such that the cued location was now illuminated in average sunlight. Finally, the target, an annulus that matched the prime either in terms of surface or reflected color, was presented at the cued location. Participants were timed to respond to the color of the annulus: either green or blue.

Overall, the results were clear in showing something called a *surface priming advantage*—participants were speeded in responding to the target annulus when it matched the prime's surface color and not its reflected color. There was no corresponding speeding on trials in which the prime matched the reflected color of the annulus. The results were taken to show that such a surface priming advantage could only arise if the surface reflectance properties of the prime were recovered very rapidly. The effects obtained when the primes were presented very briefly (for 12.5 ms), and when participants were unable to reliably report whether a prime had been presented at all; that is, the effects arose unconsciously.

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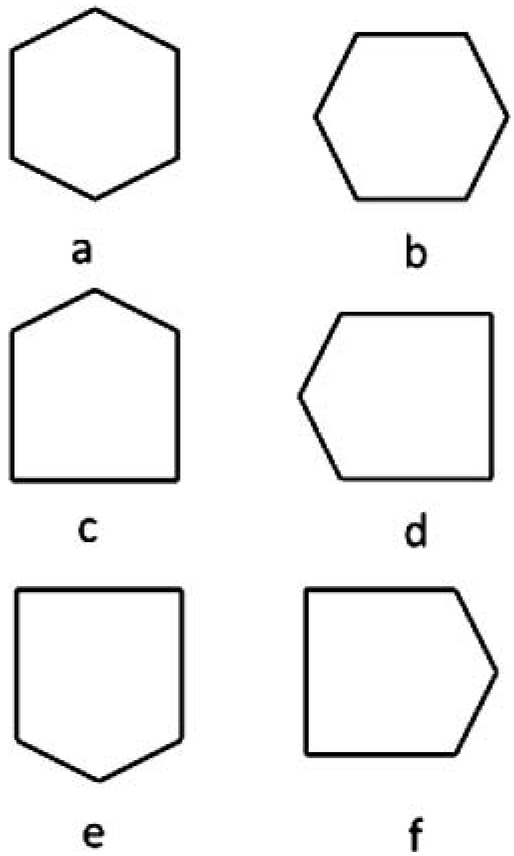

Figure 1. The actual set of target shapes used in Experiments 1 through 3.

Given the conclusions that color constancy operates both rapidly and unconsciously, we can ask comparative questions about the operation of shape constancy mechanisms. There is some evidence suggesting that there are profound differences between these two perceptual constancies. Leibowitz and Bourne (1956), for instance, found that when a shape (a circular disc) was rotated in depth and was presented for 100 ms or less, then reports of perceived shape aligned with the projective shape (an ellipse) rather than objective shape (a circle). This is an indication that attaining shape constancy takes considerably more time than the very brief intervals reported by Norman et al. (2014): In the Norman et al. (2014) study the stimulus onset asynchrony (SOA) between the prime and target was held constant across trials at 50 ms, but the duration of the prime itself varied. Critically, the surface priming advantage obtained when the prime itself was present for only 12.5 ms. Indeed others have reported that color constancy can be achieved with displays presented for as little 1 ms (see Foster, Craven, & Sale, 1992).

Further evidence reported by Epstein and colleagues converged on the conclusion that effects of shape constancy only emerge at much greater durations—that is, $\geq$80 ms (Epstein & Hatfield, 1978; Epstein, Hatfield, & Muise, 1977; Epstein & Lovitts, 1985). Indeed, in sketching a model of shape constancy, Epstein and Lovitts (1985) argued that what is recovered initially is a representation of the projective properties of an input shape and that further operations are then applied so as to recover its objective properties. So, with our circular disc example, the initial registration will be of an ellipse and then further operations are needed to embellish this two-dimensional (2-D) projection with information about depth and distance of the surface from the viewer. Once these operations have been applied, then what is perceived is a circle at a particular slant.

Cast in this way there appears to be a clear difference between how the different constancies operate. For color, the results reported by Norman et al. (2014) suggest that the initial registration is of surface color, that is objective color, whereas for shape, the extant data suggest that the initial registration is of projective and not objective shape. In a bid to examine this further, the present work addresses shape constancy using priming techniques inspired by those used by Norman et al. (2014).

The present experiments

The present experiments follow on directly from the work of Humphreys and Quinlan (Humphreys, 1983, 1984; Humphreys & Quinlan, 1988) on shape priming. In the study reported by Humphreys and Quinlan (1988), the intention was to explore the claim that shape constancy mechanisms operate with respect to salient axes in the case of simple geometric shapes (cf. Marr, 1982). In general terms, for shapes that possess a salient axis of symmetry and/or elongation, the claim is that this acts as a shape-based coordinate system for deriving a canonical description of the shape that is invariant with respect to view (Marr & Nishihara, 1978). For instance, the pentagon (see Figure 1c through f) possesses a single and salient axis that is both an axis of symmetry and elongation. In this regard, the shape is an *unambiguous shape* because the same axis-based description will be derived for all rotations of the shape relative to its salient intrinsic axis. In contrast, the hexagon is known as an *ambiguous shape* because it possesses many intrinsic axes of symmetry, any of which could provide a coordinate system for deriving a shape description. In particular, two different descriptions of this shape are possible depending on which axis of symmetry coincides with the vertical meridian.

The use of the terms “ambiguous” and “unambiguous” have a particular application given Marr’s (1982) theory. If a shape has a single salient internal axis of symmetry/elongation (see Humphreys & Quinlan, 1987; Quinlan & Humphreys, 1993), then there is no ambiguity as to which axis is key. An ambiguous shape is where there is more than one potential axis that can be used to establish a coordinate system for describing the shape's contour.

It should be noted that there is a sense in which all of the shapes in Figure 1 are ambiguous, because they are consistent with the back projection of a bounded contour of a solid three-dimensional (3-D) shape (i.e., a cube). But in the absence of further cues to surface depth and distance, our assumption is that the default is for the perceptual system to proceed initially on an interpretation framed in terms of a fronto-parallel projection of a 2-D planar figure (Epstein & Hatfield, 1978; Epstein et al., 1977; Epstein & Lovitts, 1985). This assumption is tested in the following. In advance, however, it is worth noting that when normal controls were tested with silhouettes of common 3-D objects, performance on simple object naming tasks was far from perfect and was exquisitely sensitive to angle of regard (see Warrington & James, 1986); in other words, recovering a 3-D interpretation of a bounded contour appears to be both effortful and error-prone.

Comparing across Figure 1a and b, it can be seen that across a and b different internal axes of symmetry of the shape align with the vertical meridian. In such cases and following on from the work of Humphreys (1983), different shape descriptions for the two orientations of the hexagon will be derived in the respective cases. In contrast, comparing across Figure 1c through f, given that the pentagon possesses only a single salient axis, then this will operate as the same coordinate system regardless of its orientation. Hence the same shape description will be derived for the different orientations.

In following up on this line of reasoning, Humphreys and Quinlan (1988) examined shape priming in cases where both the prime and target shapes were highly visible. In their experiment 5b, prime shapes were presented for 200 ms and were unmasked. Following the offset of the prime an interstimulus interval of 200 ms occurred and then the target shape was presented for 200 ms. The shapes used are shown in Figure 1 (i.e., instances a through d), and, on each trial, participants made a five- versus six-sided speeded decision once the target had been presented. Performance was examined across a number of different priming conditions. A neutral baseline condition was where the prime was a row of *x*'s rather than a shape. Another control condition was where the prime was a circle (i.e., a shape unrelated to the designated responses). In an identical condition, the prime and target were the same shape in the same orientation. In a different condition the prime was a hexagon and the target was a pentagon (or vice versa). Finally, in the within-plane transformed condition, the prime and target were instances of the same shape but the prime was rotated 90° within the plane relative to the target.

A key prediction was made on the basis of the axis-based theory, namely, that substantial priming would be obtained for the pentagon in the within-the-plane rotation condition but not for the hexagon. The reasoning was simply that for the pentagon the same axis-based description would be derived for both the rotated prime and the target but that different axes-based descriptions would be derived for different rotated versions of the hexagon. This prediction was supported in the data. That is, relative to performance in the neutral (row of *x*'s) baseline condition, there was statistically significant speeding in the within-the-plane condition for the pentagon trials but not for the hexagon trials. Other results, that will be returned to later, were (a) large repetition priming effects in the data for both shapes, and (b) response slowing (relative to the neutral baseline) when the prime and target were different shapes. Notably, the effects were manifest at relatively long durations (i.e., an SOA of 400 ms between the prime and the target) and when primes were visible and unmasked. The present work begins with an exploration of the operation of such mechanisms when very brief and masked stimulus presentations are used.

In the present case, and following on from Norman et al. (2014), any priming effects will be expressed in terms of RTs (i.e., reaction times) relative to a no prime condition (rather than the kind of neutral condition used by Humphreys & Quinlan, 1988). In general, response speeding relative to a no-prime condition is taken to reflect common processes and representations that underlie the recovery of information of both the prime and the target. In contrast, slowing relative to a no-prime condition is evidence that the recovery of information about the prime and target reflects different internal representations and processes.

Following Humphreys and Quinlan (1988), it is accepted that such priming effects provide evidence of the operation of shape constancy mechanisms. There is no implication that the *only* way in which shape constancy is achieved is via the sorts of axis-based operations discussed by Marr (1982; see Humphreys & Quinlan, 1987, for a thorough discussion of the alternatives). Nonetheless, a substantial amount of behavioral evidence exists that underscores the importance of axis-based operations in the perception of 2-D geometric shapes (see Humphreys, 1983; Humphreys, 1984; Humphreys & Quinlan, 1987; Humphreys & Quinlan, 1988; Quinlan, 1991; Quinlan, 1995; Quinlan & Humphreys, 1993). Internal axes of symmetry and/or elongation are of some perceptual significance and do appear to play some role in supporting constancy.

Although the empirical/theoretical backdrop to the present work traces back to the 1980s, it is notable that little further work has followed up on the very particular issues concerning shape constancy addressed here. Instead the key issues have concerned 3-D object recognition and, in particular, the recognition of familiar objects. In this regard, the work has examined performance with line drawings and/or photo images of familiar objects (e.g., see Biederman & Ju, 1988) and the theoretical emphasis has been with issues concerning the recognition of multicomponent objects (e.g., see Biederman, 1987). Despite the change in emphasis, priming studies have featured heavily in the literature (Bar & Biederman, 1998; Biederman & Cooper, 1991, 2009; Biederman & Gerhardstein, 1993; Fiser & Biederman, 2001; and more recently, Vuilleumier, Henson, Driver, & Dolan, 2002). Here we limit ourselves to examining how priming can elucidate processes involved in shape constancy. More particularly, we examined this in terms of assumptions about rigidity.

Although it is not universally true that solid objects are rigid, rigidity is a fundamental aspect of shape constancy. Via priming, we examined the contrast between shape transformations that honor rigidity and those that do not. The rigid transformations we examine here are through-the-plane rotations (i.e., rotations around the y-axis). If the prime and target are related by a through-the-plane rotation, the prime–target relationship supports shape constancy (cf. Humphreys & Quinlan, 1988). In contrast, if the prime is a stretched (shear) version of the target, then the prime and target are related by a nonrigid transformation that violates shape constancy. The expectation was that RT speeding (i.e., positive priming) should be obtained if the prime and target are associated by a rigid, but not a nonrigid, transformation. We claim that such a pattern of performance would provide further insights into the operation of shape constancy mechanisms and, indeed, mechanisms that are not solely reliant on the recovery of intrinsic axis-based shape descriptions.

In total, five shape priming experiments are reported here and because they are all very similar, it is parsimonious to convey the common characteristics first and then proceed onto the experiment-specific details.

General methods

All of the experiments were controlled by bespoke programs written in PsychoPy version 84.2 (Peirce, 2007). The events on a trial were as follows. A central fixation dot was presented for ~500 ms (Display 1), and this was immediately followed by a prime shape for 13.3 ms (Display 2). For the masking experiments (i.e., Experiments 1 and 2) the next display contained a visual noise mask (i.e., Display 3) but for the other, no-mask experiments (i.e., Experiments 3 and 4) the next display (Display 3) was blank. The duration of Display 3 varied across experiments. Finally, a five- or six-sided shape (the target) was presented (in Display 4) until response. On every trial the participant made a key press response under RT instructions as to whether the target was a five- or six-sided figure. Once a response had been detected there was an intertrial interval of ~500 ms.

Equipment

The same equipment was used throughout. All stimuli were presented on a Mitsubishi Diamond Plus 91 monitor (Mitsubishi Electric Corporation, Tokyo, Japan) with a frame rate of 13.3 ms (i.e., 75 Hz). Timings were independently checked with the Black-Box toolkit (The Black Box Toolkit Ltd., Sheffield, UK; see Plant & Quinlan, 2013). The screen resolution was set at 1,600 × 1,200 pixels. Participants' viewing distance was controlled via a height-adjustable chin rest fixed 60 cm from the screen. A Cedrus response box (Model RB-520; Cedrus Corporation, San Pedro, CA) was used to collect all responses with the actual responses picked up via presses on the left or right key. In all cases the left finger key was designated the five-sided button and the right finger key was designated the six-sided button.

Stimuli and design

The central fixation point was a small white circle, 0.08° in diameter (in all displays the background was black). In Experiments 1 through 3 two geometric shapes were used as the target shapes: a regular hexagon and five-sided figure (the pentagon) based on the hexagon in Figure 1 (for the complete set of target shapes used, see Humphreys & Quinlan, 1988). All target shape contours were rendered as white (in terms of PC color codes, the color was "White"). Target shapes were defined within a virtual circle, 3.1° in diameter. The contour was 0.04° (i.e., 2 pixels) thick. Prime shapes were defined relative to a virtual circle, 2.5° in diameter. Again, the prime's contour was 0.04° thick. In a bid to render the prime difficult to see, the contour of the prime shape was presented in PC color "DimGray" at a lower contrast than the "White" of the target. The contours of the shapes were antialiased.

Both target and prime shapes were centered and, had both been presented simultaneously, then the prime would appear inside the contour of the target. This was, in part, to avoid any possible residual masking effects

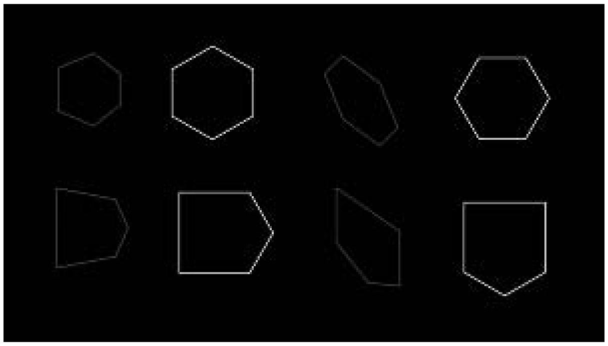

Figure 2. Examples of the sorts of primes and targets used in the first four experiments. The figure comprises four prime-target pairs—upper-left, a through-the-plane rotated hexagon and its corresponding target; upper-right, a stretched hexagon and its corresponding target; lower-left, a through-the-plane pentagon and its corresponding target; lower-right, a stretched pentagon and its corresponding target.

of the target on the prime, and also to mimic the displays used by Norman et al. (2014) in which the prime corresponded to the hole of the target annulus. For the masking experiments (i.e., Experiments 1 and 2), Display 3 contained a visual noise mask as defined in the masking demo distributed with PsychoPy (Peirce, 2007). The mask spanned a centered square region (5.3° × 5.3° in extent).

There were five basic conditions of interest and these were individuated with respect to a given type of trial (henceforth, simply *trial type*). In all cases, the target shape was one of the shapes shown in Figure 1. In the no-prime condition, Display 2 was left blank. In the rigid condition, the prime shape was a rigid transformation of the target shape. In the nonrigid condition, the prime shape was a shear transformation of the target shape. In the repetition condition, the prime and the target were versions of the same shape in the same orientation. In the different condition, the prime and target shapes were different with respect to their number of sides: So, if the prime was a pentagon, the target was a hexagon, and vice versa.

For the rigid transformation, the target shape was reduced slightly in size and then rotated through the *y*-axis by a random angular displacement taken within the range 15°–30°. The through-the-plane rotation itself was then implemented, at random, in a leftwards or rightwards direction.[1] For the nonrigid transformation, the target shape was again reduced in size and then a shear transformation in the range 0.5–0.75 was applied. The direction of the shear (*x* or *y*) was chosen at random. Although primes were size-reduced versions of their corresponding targets (after Norman et al., 2014), with some of the extreme transformed cases, parts of the prime's contour did extend beyond the contour of the target. Figure 2 provides examples of the sorts of primes and targets used in the two transformation priming conditions.

Participants

In all cases the participants were recruited from a web-based system in which anyone within The University of York can sign up for experimental testing in the Department of Psychology. As a consequence, all of the participants were taken from this university community. Some of the participants were undergraduates from the psychology department and received course credit while others were simply paid for taking part. All participants were tested individually in a dimly lit testing room. Testing typically lasted no longer than 30 min. A stopping rule (Simmons, Nelson, & Simonsohn, 2011) of 20 participants was adopted for all experiments. This is over twice the number of participants tested by Humphreys and Quinlan (1988) in their experiment 5b.

Experiment 1: Short prime/target interval including a mask

In the first experiment the prime duration was set at one frame (i.e., 13.3 ms) and the ensuing mask duration was set at three frames (i.e., 39.9 ms). These display timings were governed by consideration of the color constancy effects reported by Norman et al. (2014), which showed a surface color advantage when the prime was presented for 12.5 ms and the target followed after 31.3 ms. In addition, Norman et al. (2014) showed that the effects arose under conditions in which the prime was rendered invisible: In a separate experiment, they found that, in using the same display characteristics, participants were unable to detect the presence of the prime.

In the present case, the presence of the prime was rendered difficult, if not impossible, to detect: first by presenting it at low contrast, and second by following it by a visual noise mask. Some participants did report seeing a fleeting impression of a prime shape on one or two trials when quizzed after testing. Given that most participants never reported seeing any of the primes, in general the conclusion was that participants did not see the primes, and no further investigation of the prime's visibility was attempted. Issues concerning prime visibility will be returned to as the material unfolds. For the no-prime trials, the mask was simply presented for four frames (i.e., 53.2 ms).

To reiterate, evidence for the operation of shape constancy mechanisms would be revealed by positive

Trial type	Mean RT	*SE*	Proportion of errors	Proportion of outliers
Pentagon				
No prime	522	16	0.03	0.03
Rigid	517	16	0.04	0.03
Nonrigid	524	16	0.04	0.03
Repetition	525	16	0.03	0.03
Different	527	15	0.04	0.03
Hexagon				
No prime	537	26	0.03	0.03
Rigid	541	25	0.03	0.03
Nonrigid	515	16	0.03	0.03
Repetition	516	18	0.03	0.03
Different	533	24	0.03	0.03

Table 1. Descriptive statistics for the conditions of interest in Experiment 1. *Notes*: RT = reaction time; *SE* = standard error.

priming in the rigid condition together with no such effect in the nonrigid condition. Moreover, from the work of Humphreys and Quinlan (1988), it is predicted that strong positive priming should be obtained in the repetition condition and response slowing (relative to the no prime condition) should be revealed in the different condition.

Method

Design and Procedure

In the experiment proper, a block of 24 practice trials preceded four blocks of 96 experimental trials. The number of trials was based on multiples of a basic set of 24 trials. As Figure 1 shows, there were two tokens of the hexagon (a and b) but four tokens of the pentagon (c through f) that acted as targets. To even up the number of five- and six-sided targets, trials associated with a and b were doubled. For each of these eight targets (i.e., a, a, b, b, c, d, e, f), one trial was taken from the rigid, nonrigid, and repetition conditions and two trials were taken from the different condition. In this way on one third of the trials, the prime and target were shapes with different numbers of sides. This was to mitigate against generic response priming. So, for each of the eight targets there was an associated set of six trials giving an overall basic set of 32 trials.

The practice trials were simply a random selection taken from the basic 32, whereas the experimental trials were generated by randomizing the set of 32 three times and concatenating this list to give rise to 96 experimental trials.

Participants

Twenty participants were tested, and their average age was 19.5 years.

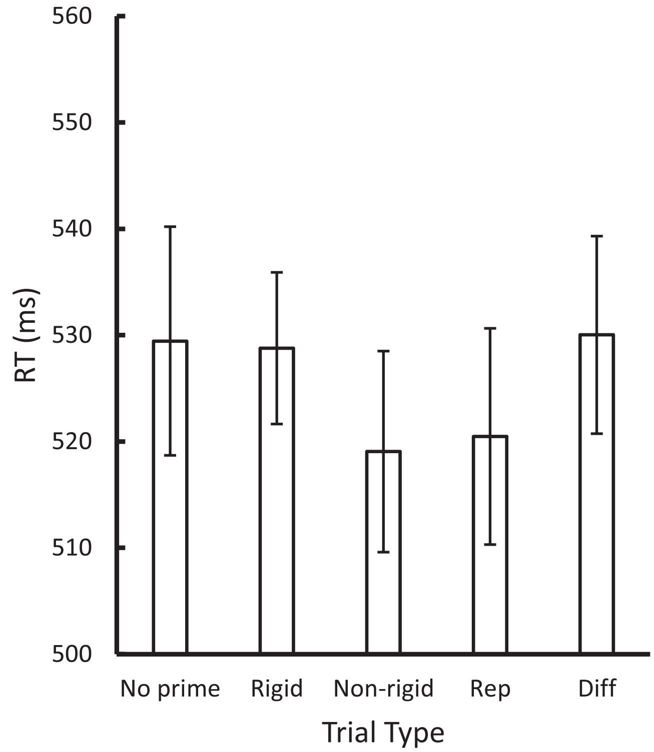

Figure 3. Mean RTs for the five trial types in Experiment 1. Error bars reflect within-participant 95% confidence intervals as defined by Bakeman and McArthur (1996). Rep = repetition condition; Diff = different condition.

Results and discussion

For all experiments the data were scored as follows. In the RT analyses only the data from correct trials were considered. For each participant, mean RTs per condition were calculated and then any outliers (± 2.5 *SD*s from these condition means) were removed. The descriptive statistics for corresponding conditions are reported in Table 1. In reporting the results of the analyses of variance (ANOVAs) the Greenhouse-Geisser correction has been applied to tests where the assumption of sphericity was violated.

Figure 3 shows a graphical illustration of the summary RT data for the different trial types. The RT scores were entered into a 2×5 repeated-measures ANOVA in which number of sides (five vs. six) and trial type (no-prime, rigid, nonrigid, repetition, and different) were entered as fixed factors and participants acted as a random factor. This analysis failed to reveal any statistically reliable results: $F(1, 19) = 0.248$, $p > 0.05$, partial $\eta^2 = 0.013$, for the main effect of number of sides; $F(4, 76) = 1.118$, $p > 0.05$, partial $\eta^2 = 0.056$, for the main effect of trial type; and $F(2.513, 60.591) = 2.768$, $p > 0.05$, partial $\eta^2 = 0.127$, for the number of sides $\times$ trial type interaction.

In order to examine the null effects in more detail the data were examined further using Bayesian methods

(Rouder, Morey, Speckman, & Province, 2012). The RT data were entered into a Bayesian repeated-measures ANOVA (JASP Team, 2017: JASP 0.8.1.1) in which the same factors of number of sides, priming condition, and participants were as defined for the traditional ANOVA just reported.

Relative to the null model (in which equality is assumed across all cells in the design) a full model comprising the main effects and two-way interaction generated an inverse Bayes factor of 0.003. That is, there was "decisive" evidence against the full model relative to the null model (Wetzels et al., 2011). As a consequence, we conclude that the data provide *decisive* evidence that there were no effects of type of shape nor type of prime in the data.

As Table 1 shows, error rates were noticeably low (all ≤ 0.04) and there was no evidence of any systematic speed/error trade-offs. On these grounds the accuracy data are reported but were not analyzed.

In sum, the data from Experiment 1 failed to show any condition effects. Most particularly, there was no evidence of any priming effects relative to the no-prime condition. When the prime shape was presented very briefly, masked, and then followed very briefly by a target shape, the presence of the prime had no detectible effects on the processing of the target. This is evidence that the mechanisms of shape constancy are unlike those found for color constancy as reported by Norman et al. (2014). In addition, there is apparently no evidence that shape constancy is achieved unconsciously in a manner that is consistent with the operation of color constancy (cf. Norman et al., 2014).

Experiment 2: Longer prime/target interval including a mask

In some regards we might argue that our use of a visual noise mask has been too effective because the data in Experiment 1 failed to show any effects due to the presence of a prime. To explore the issues further we note a distinction made by Epstein et al. (1977) between *exposure time* and *processing time* (p. 474). In their study in a pretest set of trials, participants made judgments about the rotated ellipses when the exposure time of the ellipse was varied. In this way, the minimum exposure duration for achieving shape constancy was ascertained on a participant-by-participant basis. In a separate set of trials visual masking was used such that the target shape was presented for the participant's own minimum exposure, but the mask was presented either concurrently with the onset of the shape or after a delay of 25 or 50 ms. The understanding was that the mask would selectively limit *processing* time. That is, the mask would in some way disrupt processes responsible for shape constancy. The results showed, quite conclusively, that the presence of the mask severely disrupted processing: Judgments tended away from the objective to the projective shape even though the shape itself was presented for the same fixed exposure time.

In the current Experiment 1, the mask followed the prime immediately at the prime's offset, hence it might be argued that the exposure time and the processing time were of the same brief interval. However, it is also possible that prime processing continued after its onset, and regardless of the mask, but that this was interrupted because of the sudden onset of the target: The target was presented within 50 ms of the prime's offset. In exploring this possibility, in Experiment 2, the onset of the prime and the mask were the same as in Experiment 1, but now the target was delayed for an additional 53.2 ms. On priming trials, the prime was presented for 13.3 ms and the mask was presented for 93.1 ms. An assumption was that any constancy mechanisms entrained by the presentation of the prime might need more than 50 ms to complete (cf. Leibowitz & Bourne, 1956). Hence by increasing the delay between the prime and target (and therefore processing time), it was predicted that any possible effects due to the various shape primes would more readily be witnessed than in Experiment 1.

Method

The identical methods used in Experiment 1 were repeated with the key change between the two studies being the delay between the offset of the prime and the onset of the target. On the prime trials, the prime was presented for 13.3 ms and the mask was presented for 93.1 ms. On the no-prime trials the mask immediately followed the fixation point and was presented for 106.4 ms.

Participants

The study was run with 20 participants whose average age was 20.05 years.

Results and discussion

The RT scores were analyzed as in Experiment 1, and again, the analysis failed to reveal any statistically reliable results: $F(1, 19) = 1.146$, $p > 0.05$, partial $\eta^2 = .057$, for the main effect of number of sides; $F(2.602, 49.442) = 2.832$, $p > 0.05$, partial $\eta^2 = 0.130$, for the main effect of trial type; and $F(4, 76) = 2.147$, $p > 0.05$, partial $\eta^2 = .102$, for the number of sides $\times$ trial type interaction. Table 2 provides descriptive statistics for

Trial type	Mean RT	*SE*	Proportion of errors	Proportion of outliers
Pentagon				
No prime	544	25	0.02	0.03
Rigid	528	22	0.03	0.03
Nonrigid	543	23	0.03	0.03
Repetition	512	19	0.02	0.03
Different	542	25	0.02	0.03
Hexagon				
No prime	536	24	0.04	0.03
Rigid	518	18	0.04	0.03
Nonrigid	520	22	0.04	0.03
Repetition	528	25	0.03	0.03
Different	537	24	0.04	0.03

Table 2. Descriptive statistics for the conditions of interest in Experiment 2. *Notes*: RT = reaction time; *SE* = standard error.

the conditions of interest and Figure 4 provides a graphical illustration of the summary RT data for the different trial types.

Again, the data were further examined via Bayesian techniques in the same manner as before. Now the analysis revealed that, relative to the null model, a full model comprising the main effects and two-way interaction generated an inverse Bayes factor of 0.171. That is, there was only anecdotal evidence against the full model relative to the null model (Wetzels et al., 2011). As a consequence, we conclude that the data provide only anecdotal evidence that there were no effects of type of shape or type of prime.

In sum, the data provide little indication of any systematic priming effects. Although the evidence is "anecdotal" rather than "decisive," this did not generate a compelling case for repeating the experiment with a larger sample of participants. Looking across the data for Experiments 1 and 2, we conclude that we have failed to find any shape priming effects indicative of shape constancy when primes were presented briefly and were masked. These findings contrast starkly with those reported by Humphreys and Quinlan (1988), and we take it that this reflects the differences in the displays and display timings used in the two studies. In the Humphreys and Quinlan (1988) experiment 5b the primes were presented for 200 ms, were unmasked, and were followed by a 200-ms blank interval prior to the presentation of the target. As a consequence, in the Humphreys and Quinlan (1998) case, both exposure and processing times were considerably longer than those used here.

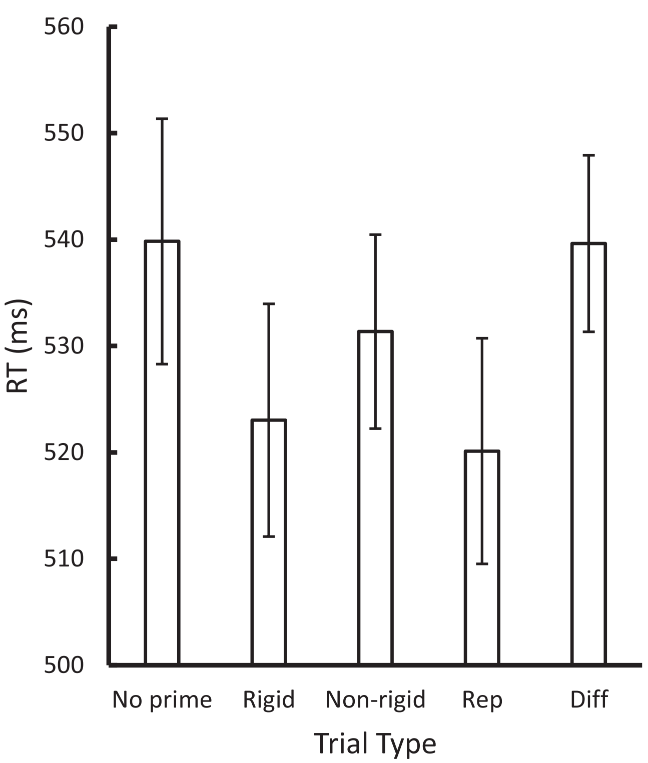

Figure 4. Mean RTs for the five trial types in Experiment 2. Error bars reflect within-participant 95% confidence intervals as defined by Bakeman and McArthur (1996). Rep = repetition condition; Diff = different condition.

Experiment 3: Longer prime/target interval excluding a mask—regular shapes

Rather than alter both the timings and the presence of a mask, in Experiment 3 we decided to retain the timings used in Experiment 2 but remove the visual noise mask. Where previously a mask had been used on every trial, now this was replaced with a blank field. In this way, the primes although briefly presented, were clearly visible. In all other regards, the experimental methods were the same as before.

Participants

Twenty-one participants were tested initially, but the data from one participant was replaced due to a failure to comply with the instructions. The average age of the eventual sample of 20 was 19.65 years.

Results and discussion

The RT scores were analyzed as previously. Now the analysis revealed statistically reliable main effects of both number of sides, $F(1, 19) = 16.136$, $p = 0.001$, partial $\eta^2 = 0.459$, and trial type, $F(2.872, 54.568) = 73.000$, $p < 0.001$, partial $\eta^2 = 0.793$, and $F(4, 76) =$

Trial type	Mean RT	*SE*	Proportion of errors	Proportion of outliers
Pentagon				
No prime	497	17	0.03	0.03
Rigid	473	20	0.02	0.03
Nonrigid	508	18	0.03	0.02
Repetition	444	22	0.01	0.03
Different	525	17	0.04	0.03
Hexagon				
No prime	472	18	0.02	0.03
Rigid	448	17	0.01	0.03
Nonrigid	472	17	0.01	0.03
Repetition	418	18	0.01	0.03
Different	512	15	0.05	0.03

Table 3. Descriptive statistics for the conditions of interest in Experiment 3. *Notes*: RT = reaction time; *SE* = standard error.

1.895, $p > 0.05$, partial $\eta^2 = 0.091$, for the number of sides × trial type interaction. Table 3 provides descriptive statistics for the conditions of interest and Figure 5 provides a graphical illustration of the summary RT data for the different trial types.

The main effect of number of sides revealed that participants were generally quicker to respond to the hexagon targets (464 ms) than the pentagon targets (489 ms). This may reflect the fact that whereas only two tokens of the hexagon target were ever presented, there were four versions of the pentagon (see Figure 1). The statistically reliable effect of condition was examined further via a series of planned contrasts. Performance in each of the four priming conditions was compared against that in the no prime condition. These contrasts revealed statistically reliable speeding of responses in the rigid, $t(19) = 4.061$, $p = 0.001$, and, the repetition conditions, $t(19) = 9.818$, $p < 0.001$, and statistically reliable slowing of responses in the different condition, $t(19) = -7.308$, $p < 0.001$. There was no statistically reliable priming effect in the non-rigid condition, $t(19) = -0.795$, $p > 0.05$.

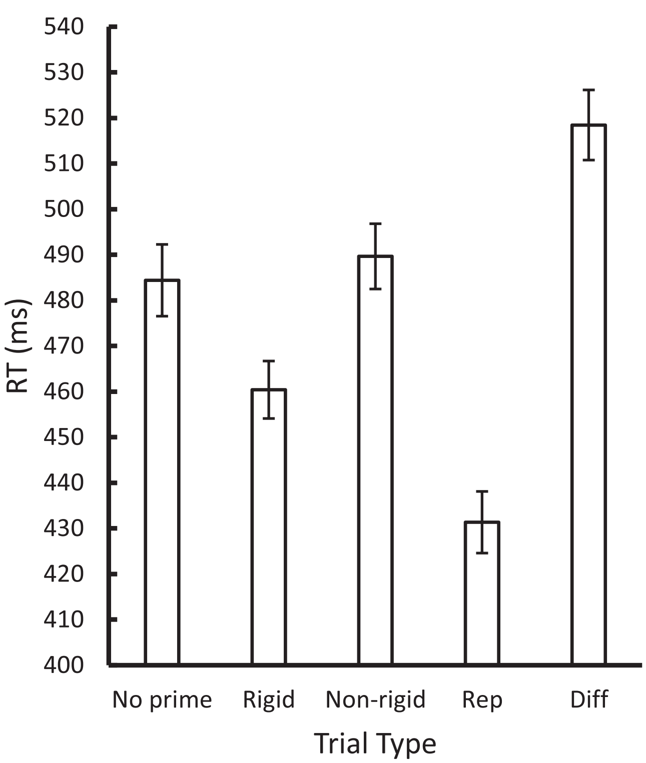

Figure 5. Mean RTs for the five trial types in Experiment 3. Error bars reflect within-participant 95% confidence intervals as defined by Bakeman and McArthur (1996). Rep = repetition condition; Diff = different condition.

With regard to the first of the two effects, the data from the repetition condition reveals that participants were facilitated in responding (relative to the no prime baseline) when the prime and target shapes were identical. Next, participants were correspondingly slow to respond in the different condition when the prime and target were different-sided shapes. Both the speeding in the repetition condition and the slowing in the different condition replicate similar findings reported by Humphreys and Quinlan (1988, experiment 5b). Moreover, both of these effects reveal that evidence of the operation of shape-sensitive mechanisms can be found even when the prime is briefly presented and the delay between the prime and target is also very brief.

More important, though, are the data from the other two transformation conditions. Whereas there was statistically reliable and positive priming in the rigid condition, no priming effects arose in the data for the nonrigid condition. In other words, when the prime was a rigid rotation of the target then responses were facilitated relative to the no-prime condition. We take it that this pattern of effects provides support for the idea that if the prime and the target are rigid transformations of one another then they both invoke the same shape constancy mechanisms. Critically such constancy mechanisms fail if the prime and target are nonrigid transformations of one another.

Experiment 4: Short prime/target interval excluding a mask—regular shapes

Given that the data from Experiment 3 reveal reliable priming effects at the longer SOA, Experiment 4 was carried out to see whether similar effects would be obtained at the short SOA in the absence of the

Trial type	Mean RT	*SE*	Proportion of errors	Proportion of outliers
Pentagon				
No prime	464	11	0.02	0.03
Rigid	448	9	0.04	0.02
Nonrigid	486	11	0.04	0.02
Repetition	429	10	0.02	0.04
Different	501	9	0.08	0.03
Hexagon				
No prime	454	17	0.03	0.03
Rigid	431	12	0.03	0.03
Nonrigid	476	11	0.04	0.03
Repetition	425	18	0.03	0.03
Different	500	11	0.07	0.03

Table 4. Descriptive statistics for the conditions of interest in Experiment 4. *Notes*: RT = reaction time; *SE* = standard error.

visual mask. The stimulus timings were those used in Experiment 1 in which the prime duration was set at one frame (i.e., 13.3 ms) and the ensuing blank duration was set at three frames (i.e., 39.9 ms). On no-prime trials the blank interval was set at four frames (i.e., 53.2 ms). In all other regards, the experimental methods were the same as before.

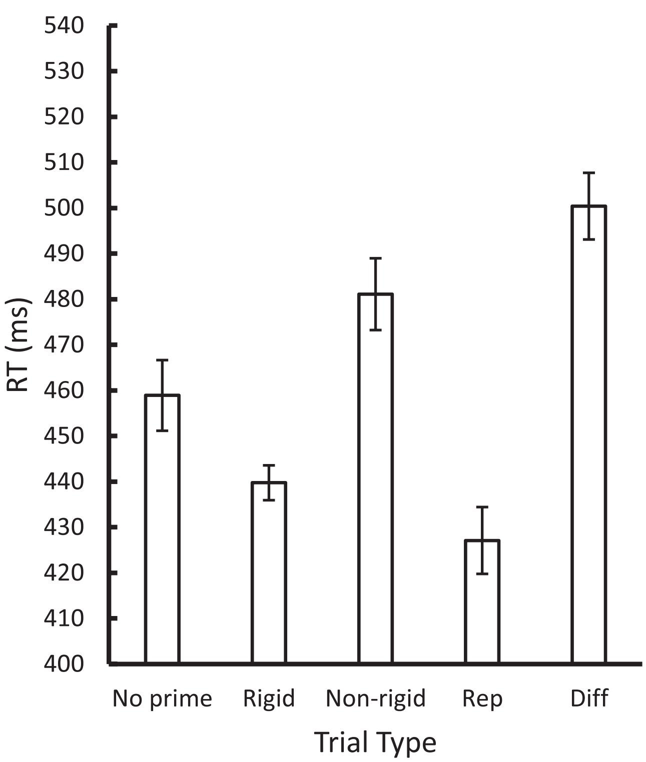

Figure 6. Mean RTs for the five trial types in Experiment 4. Error bars reflect within-participant 95% confidence intervals as defined by Bakeman and McArthur (1996). Rep = repetition condition; Diff = different condition.

Participants

Twenty participants were tested with an average age of 21 years.

Results and discussion

The RT scores were analyzed as previously. Now the analysis revealed that only the main effects trial type, $F(1.768, 33.593) = 64.042$, $p < 0.001$, partial $\eta^2 = 0.771$, reached statistical significance; $F(1, 19) = 1.440$, $p > 0.05$, partial $\eta^2 = 0.070$, for the main effect of number of sides; $F < 1.0$, for the number of sides $\times$ trial type interaction. Table 4 provides descriptive statistics for the conditions of interest and Figure 6 provides a graphical illustration of the summary RT data for the different trial types. The statistically reliable effect of condition was examined further via planned contrasts as before. The contrasts revealed statistically reliable speeding of responses in the rigid, $t(19) = 4.174$, $p = 0.001$, and, the repetition conditions, $t(19) = 10.734$, $p < 0.001$, and statistically reliable slowing of responses in the nonrigid, $t(19) = -3.124$, $p < 0.01$, and, different conditions, $t(19) = -6.260$, $p < 0.001$.

Comparing Figures 5 and 6 reveals the striking similarities in performance across Experiments 3 and 4. There was positive priming on the rigid trial types but not the nonrigid trial types. In addition, there was response speeding on repetition trials and response slowing on different trials (both effects replicate the earlier findings of Humphreys and Quinlan, 1988). We take it that the positive priming on rigid trials is indicative of the operation of shape constancy mechanisms, and given that these have obtained at the short prime–target interval used in Experiment 4 (i.e., at ~50 ms), then we conclude that the evidence is for the rapid initiation of shape constancy at durations of less than 100 ms, contrary to the findings of Leibowitz and Bourne (1956). This point will be returned to in the General discussion.

Experiment 5: Longer prime/target interval excluding a mask—perturbed shapes

Experiment 3 revealed patterns of performance in line with our expectations regarding the primacy of shape constancy mechanisms, and Experiment 4 revealed that these effects occur rapidly. In both cases, priming effects arose when the prime and targets were associated by a rigid but not a nonrigid transformation. Critically, we have shown such effects when the primes

Trial type	Mean RT	SE	Proportion of errors	Proportion of outliers
Pentagon				
No prime	602	20	0.04	0.03
Rigid	576	25	0.04	0.03
Non-rigid	599	26	0.04	0.03
Repetition	534	20	0.03	0.03
Different	584	16	0.05	0.03
Hexagon				
No prime	594	24	0.02	0.04
Rigid	571	26	0.03	0.04
Nonrigid	607	35	0.03	0.03
Repetition	560	31	0.02	0.04
Different	606	21	0.04	0.04

Table 5. Descriptive statistics for the conditions of interest in Experiment 5. *Notes*: RT = reaction time; *SE* = standard error.

are visible and not masked. Given the lack of any priming effects in Experiments 1 and 2 and presence of priming effects in Experiments 3 and 4, it seems as though the presence of the visual noise mask severely disrupted the operations of the shape constancy mechanisms. It is not mere exposure time that is critical but the presence of a mask.

In a bid to garner further evidence for these conclusions, we carried out a partial replication of Experiment 3. We retained the display timings from Experiment 3, but we changed the shapes that we used. Now on every trial a new five- or six-sided shape was generated prior to every trial. In all of the experiments reported so far, tokens of the particular hexagon and pentagon shown in Figure 1 have been used. In the final experiment, we wished to explore the generality of the findings by expanding the sample of shapes used. To this end families of five- and six-sided shapes were used that were defined as perturbed versions of the hexagon and pentagon shown in Figure 1. On the assumption that the results of Experiments 3 and 4 reveal something general about shape processing, then it is assumed that the findings should replicate to cases when less familiar, irregular shapes are used.

Method

Stimuli, design, and procedure

The following method was used, prior to each trial, to generate a novel shape on every trial. The first apex for the shape was taken at random as the point on the diameter 60° ± 12° from the vertical. The next apex was chosen as being 60° ± 12° further on, and so on, until the required number of apices had been generated. This ensured that the set of shapes retained a resemblance to the actual pentagon and hexagon shown in Figure 1, but they were now irregular. Once a shape had been generated, this was then rotated within the plane by a random angle between 0° and 360°.

Now for each type of shape (five- or six-sided) a basic set of six trials was generated, including one for each priming condition and an additional trial for the different condition. In the experiment proper, a random order of these 12 trials was used as practice trials. There then followed five blocks of 120 experimental trials. Each block of experimental trials contained 10 random orders of the 12 basic trials. In total, therefore, there were 600 experimental trials and any one testing session lasted no more that 40 min.

Participants

In total 22 participants were tested, but two were replaced: one because of inaccurate responding (i.e., over 1/3 of the responses were errors) and one because of an extremely odd speed/error tradeoff (i.e., excessively long RTs with only eight errors across all 600 experimental trials). The average age of the eventual sample of 20 was 19.35 years.

Results and discussion

The RT scores were analyzed as previously. Now the analysis revealed that only the main effect of trial type reached statistical significance, $F(2.861, 54.365) = 9.420$, $p < 0.001$, partial $\eta^2 = 0.331$; $F(1, 19) = 0.416$, $p > 0.05$, partial $\eta^2 = .021$, for the main effect of number of sides; $F(2.322, 44.126) = 2.131$, $p > 0.05$, partial $\eta^2 = 0.101$, for the number of sides × trial type interaction. Table 5 provides descriptive statistics for the conditions of interest and Figure 7 provides a graphical illustration of the summary RT data for the different trial types. The statistically reliable effect of condition was examined further via planned contrasts as before. The contrasts revealed statistically reliable speeding of responses in the rigid, $t(19) = 2.713$, $p = 0.014$, and the repetition conditions, $t(19) = 6.269$, $p < 0.001$. There were no priming effects found in the data for the nonrigid condition, $t(19) = -0.418$, $p > 0.05$, or the different condition, $t(19) = 0.323$, $p > 0.05$.

As can be seen from Figure 7, and as in Experiments 3 and 4, positive priming effects were again found in the rigid and repetition conditions and there was no similar priming in the nonrigid condition. One contrasting finding is that whereas in Experiments 3 and 4 participants were slowed in responding on the different trials relative to the no-prime baseline, now there was no evidence of any response slowing in this condition. This may have been due to the overall heterogeneity of the shapes used in Experiment 5, and indeed the data are noticeably more variable in Experiment 5 than previously (cf. Table 3 with Table 5). In sum the key findings from Experiments 3 and 4 with a fixed set of

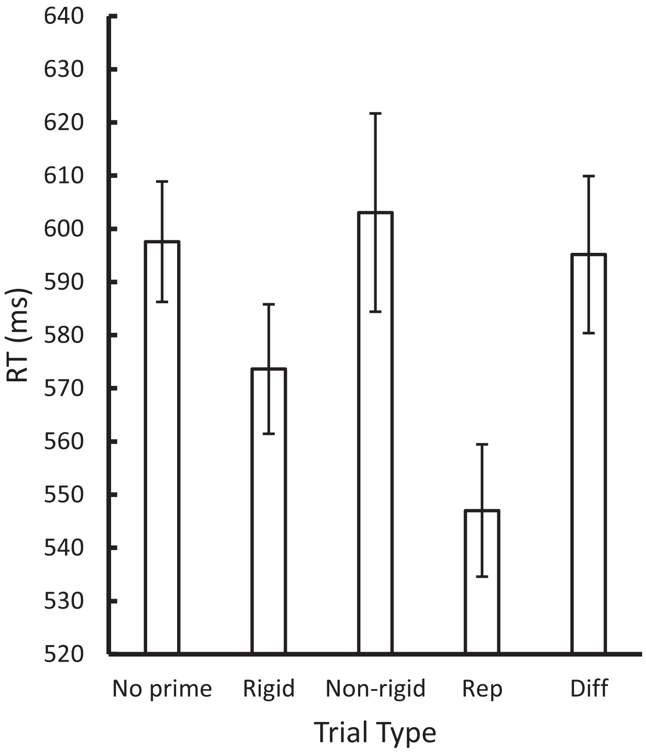

Figure 7. Mean RTs for the five trial types in Experiment 5. Error bars reflect within-participant 95% confidence intervals as defined by Bakeman and McArthur (1996). Rep = repetition condition; Diff = different condition.

shapes have generalized to conditions with novel irregular shapes.

General discussion

We have reported five shape priming experiments that have addressed issues concerning the mechanisms responsible for shape constancy. We have found that, when primes were presented briefly (i.e., for 13.3 ms) and were unmasked, then effects reflecting the operation of shape constancy mechanisms emerged. Previous research has shown that color constancy can be completed well within 50 ms even when the prime is rendered invisible by metacontrast masking (Foster et al., 1992; Norman et al. 2014). Here (in Experiment 4) effects of shape constancy have been found to emerge at approximately 50 ms. Hence both forms of constancy appear to operate within a similar, rapid time course. However, this is where the similarities with color constancy end because we found that the operations associated with shape constancy are severely disrupted by backwards visual masking. Epstein et al. (1977) argued that the presence of a visual mask disrupted the recovery of orientation information (the slant) associated with a shape, but, in the present case, the mere presence of a backward visual noise mask effectively disrupted the processing of the contour itself. The contrasting patterns of performance across the mask (Experiments 1 and 2) and the no-mask cases (Experiments 3 and 4) are striking: Whereas reliable shape priming effects were found when there was no mask, all such effects were abolished when the mask was presented.

We do not wish to argue that the operations responsible for shape constancy are open to conscious inspection, but merely that they are severely disrupted by masking that renders the primes invisible. This is quite unlike the state of affairs reported by Norman et al. (2014), for in their study the achievement of color constancy was seen to take place even when the participants were unable to detect whether a prime had been presented. We would, therefore, claim that the mechanisms for achieving shape constancy differ markedly, in nature, from those for achieving color constancy. Indeed, our data are consistent with the view that, at least in part, the operations of shape constancy are entrained by the conscious perception of shape itself.

This may seem to conflict with the findings reported by Ro, Singhal, Breitmeyer, and Garcia (2009). In their experiment 3, and on every trial, a small filled semicircle (the prime) was presented briefly (for 16.7 ms), and then following a blank display (of ~57 ms) a larger filled semicircle (the target) was presented. Given these timings the prime was rendered invisible by the target—the target acted as a backwards mask. Each semicircle was taken from one of four, which individually described the left, right, upper, and lower half of a circle, respectively. For every participant, two pairs of targets were assigned to left and right (key press) responses and RTs were measured for responses to the presentation of the target. Across trials, the prime either matched the target exactly, was congruent with the target's response, or was incongruent with the target's response. The results showed only a strong repetition priming effect such that RTs on trials where the same semicircle was repeated were significantly shorter than those on the other kinds of trials.

Ro et al. (2009) interpreted their findings in terms of the unconscious processing of shape because the presence of the target rendered the prime invisible. We have been unable to replicate these findings because we failed to find repetition priming when the prime shape was masked (i.e., in Experiments 1 and 2). However, the effects reported by Ro et al. (2009) are difficult to interpret because there is no baseline against which to compare the responses across the different sorts of prime trials. In this regard, it is impossible to tell whether there is any positive priming or whether the effects are simply due to slowing when the prime and target do not match. We also claim that identity priming may reveal very little in itself about shape constancy mechanisms. For instance, a template matching system could account for repetition priming but fail in cases where the prime and target differed in orientation.

We can ask further what the current data reveal about the detailed nature of shape constancy mechanisms. In the first four experiments, simple geometric shapes were used such that each shape possessed a salient axis of symmetry/elongation. Based on the previous work by Humphreys and Quinlan (1988), it was assumed that shape constancy for these kinds of shapes is achieved by recovering shape descriptions derived via an axis-based coordinate system. However, in the current Experiment 5, perturbed shapes were used in which symmetry and elongation were no longer consistently present. In that experiment, if a shape was symmetrical then this happened only as a consequence of the random choice of the shape's apices. On these grounds, it is difficult to argue that the results of Experiment 5 primarily reflect axis-based processes.

In discussing various accounts of shape processing, Ullman (1989) suggested that the recovery of shape information can be facilitated "if an axis ... can be identified in the image" (p. 249), and we accept this. However, it is clear that axis-based processing cannot provide a complete account of the patterns of data reported here—the same effects arose when the shapes possessed salient axes (Experiment 3) as when they did not (Experiment 5). On these grounds, therefore, we also accept that there are other means to achieve shape constancy aside from those concerning the recovery of intrinsic shape axes (cf. Humphreys, 1984, p. 63, and Humphreys & Quinlan, 1987). It is to these that we now turn.

Epstein and Lovitts (1985) provided a very general information processing account of the recovery of shape-at-a-slant. According to this model, at the earliest stage of processing, projective shape and "optical correlates of orientation" are registered automatically and independently of one another. This leads to the encoding of projective shape, and, separately, orientation information. Evidence for this claim about independent processing of shape and orientation comes from the work of Epstein et al. (1977), where they showed that masking particularly disrupted processes concerned with the recovery of orientation information. Finally, according to Epstein and Lovitts (1985), shape constancy, as defined by the recovery of objective shape, is achieved by essentially integrating projective shape information with orientation information.

We accept that at the earliest stage of processing it is projective shape that is encoded. Although the sorts of contours we have used are consistent with other interpretations such as 2-D projections of 3-D forms, our results fit most comfortably with the view that the visual system operates by first registering a representation that codes a 2-D interpretation of the input shape, particularly in cases like those used here where there are no cues to surface orientation. If there are such additional cues to depth then we accept the general claim advanced by Epstein and Lovitts (1985) that shape-from-slant operations may then be entrained so as to recover an objective representation of an oriented surface. However, our results seem to provide further evidence for the claim that any given 2-D shape representation brings with it further assumptions regarding a contingent set of possible transformations in 3-D space, of the kind discussed by Shepard (1984, 2001). In particular, as Shepard and Farrell (1985) argued, "Our seeing of objects and their motions is automatically constrained and guided by perceptual mechanisms embodying evolutionarily acquired knowledge about rigid transformations in Euclidean three-dimensional space." (p. 120; see also Kanade & Kender, 1983).

In Experiments 3, 4, and 5, the key findings were of reliable positive priming when the prime and target were related via a through-the-plane projective transformation together with no such priming when the prime and target were related via a shear transformation. The key difference between these two kinds of transformations is that with the projective projection the prime and targets are related by a rigid transformation, whereas with the shear transformation, the prime and target are related via a nonrigid transformation. We conclude, therefore, that shape processing primarily operates according to a rigidity constraint.

The view of processing that emerges is that projective shapes are initially encoded in such a way that rigidity is assumed. Such a constraint is useful in attempting to make sense of a continuously changing visual world. In integrating information over time, the visual system is attempting to recover a consistent and coherent account of the unfolding visual world based on the recovery of both variant and invariant structures in the input (see for instance, Gibson, 1986). Establishing shape constancy is an example of recovering invariant structure.

Very similar ideas can be found in Ullman's (1985) writings about interpreting visual motion, and, more generally, Ullman's (1989) perspective on shape processing provides a useful framework for thinking about the present priming effects. According to Ullman (1989), at an initial stage of processing, key features (points, elements, "anchor points," p. 216) for a shape are identified. Ullman's discussion focuses on the usefulness of determining three anchor points, but others have discussed similar schemes that depend on the recovery of six anchor points (Fischler & Bolles, 1981). Here we assume that the anchor points correspond to the apices of the shapes (for Humphreys, 1984, these are termed *focal features*). In Ullman's scheme the intention was to consider how an input shape might be matched against entries in an internal database of stored shape descriptions in a bid to account for shape identification. In simple terms, the problem reduces to one of matching the anchor points derived from the input shape with those defined for each stored model.

The method of matching is known as *alignment* in that the aim was to align the input anchor points with those of a stored model. Such matching is achieved first by applying transformations (rotations, translations and scaling) to the stored anchor points of each model and then estimating the distance between these transformed points and anchor points derived from the models. The best match is indexed by the smallest distance (see Huttenlocher & Ullman, 1990, for a detailed explication of the ideas).

In terms of the present experiments, we take it that the data do not so much reflect the matching of an input shape with a stored model, but rather an attempt to secure a match between rapid and successive presentations of two shapes. That is, the visual system attempts to solve a correspondence problem between the prime and target shapes. Although Ullman (1985) discusses this particular problem in terms of interpreting visual motion, we feel that his ideas have application in the case of the static displays used here. In the present case, a rigidity test is applied in order to establish whether the collection of identified anchor points signifies a rigid body moving through time (after Ullman, 1985, p. 146). When the visual system is able to achieve a correspondence between the prime and the target by applying the rigidity constraint this is reflected in positive priming—that is, response facilitation in the rigid conditions found here.

The general ideas can be extended to account for the processing of flexible objects "that are allowed to stretch, bend, and deform" (Ullman, 1989, pp. 223-227), but what the present data suggest is that perceptually rigid objects are treated as a being perceptually special. Although some have made a case for the usefulness of vision systems that are able to efficiently recover shape descriptions that are related by affine transformations (i.e., rotations, translations, shears, but not projective projections; see Kanade & Kender, 1983), the present work has instead emphasized the perceptual importance of transformations that preserve rigidity. In the rigid condition the prime was a projective projection of the target and there was no evidence of any response facilitation when the prime and target were related by a shear transformation.

In the earlier work by Humphreys (1983, 1984), steps were taken to rule out any role for motion mechanisms in the sorts of shape priming effects he reported. For instance, he found that impressions of apparent motion were unrelated to the shape priming effects. On these grounds, he dissociated effects due to shape recovery from those concerning motion. We accept that the operations concerning the recovery of axis-based descriptions may be quite independent of those concerning the perception of motion. However, we also accept that, more generally, shape constancy and the perception of motion may both reflect the operation of a "rigidity constraint" (Ullman, 1985). Exploring the putative links between shape and motion processing under the rigidity constraint is something that will be a focus of our future work.

We take it that the results of all of the experiments reflect shape encoding processes that give rise to a representation that captures a specification of structural rigidity. In all cases, the prime was only presented for 13.3 ms, and yet in all cases where no mask was presented, positive priming was found. In this respect, the present conclusions contrast with those of the previous work by Leibowitz and Bourne (1956) and Epstein and colleagues (Epstein & Hatfield, 1978; Epstein et al., 1977; Epstein & Lovitts, 1985), which suggests that shape constancy takes considerably longer than 50 ms to complete. It should be noted, however, that there are clear differences between the current work and earlier work. In the earlier cases actual oriented planar figures were used, whereas here 2-D projections were presented in the fronto-parallel plane. In the earlier work, therefore, the additional time to achieve constancy (i.e., to recover an impression of actual objective shape) may well reflect the time taken to integrate the surface orientation information with the projective shape information.

In the present case, and in the absence of any further cues to surface orientation, the picture that emerges is one where the system initial recovers a fronto-parallel impression of a 2-D contour (i.e., a projective shape) that in itself suggests a family of possible rigid transformations (Kanade & Kender, 1983; Shepard, 1984; Shepard, 2001; Shepard & Farrell, 1985). Whereas previously these have been discussed in terms of affine transformations, the present results indicate that it is perspective rather than affine transformations that are key. Such evidence fits well with the viewpoint consistency constraint as advocated by Lowe (1987). Low-level processes are constrained by assuming that "all projected model features in an image must be consistent with projection from a single view-point" (p. 360). Whereas Lowe (1987) made this claim with reference to securing a match between an input image and its stored model, here we make reference to the process of securing a match between two rapid presentations of two 2-D contours. The utility of this general framework for thinking has been explored by McReynolds and Lowe (1996). They developed an algorithm that uses rigidity checking as a means for securing a match between corresponding 3-D image features from a pair of 2-D views of a solid object under perspective projection.

Conclusions

In conclusion, we have provided evidence that throws further light on the mechanisms that are responsible for shape constancy. We have shown that when a briefly presented but visible prime shape is followed shortly by a target shape, then timed responses are facilitated when the prime and target are rigid transformations of one another. Such positive priming has been found when the delay between the prime and target was approximately 50 ms. No priming effects occurred when primes were rendered invisible by a backwards, visual noise mask. Previous work on color constancy has revealed that those mechanisms also operate very rapidly (Foster et al., 1992; Norman et. al., 2014), but the corresponding priming effects reported by Norman et. al. (2014) were obtained even when the primes were invisible. The contrasting patterns of performance relating to masking are intriguing and warrant further investigation.

In sum, our central findings show that the mechanisms of shape constancy are primarily constrained by factors concerning shape rigidity. There is no contradiction with the previous evidence concerning constancy operations concerning the recovery of axis-based descriptions (see Humphreys & Quinlan, 1988). Nonetheless, the priming evidence reported here is consistent across shapes that do possess salient axes and those that do not. Hence, we conclude that the human visual system apparently favors rigidity in attempting to recover invariant structures associated with distal objects.

Keywords: shape priming, shape constancy, visual noise masking, rigidity constraint

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Footnote

[1] Python code for the actual transformation was adapted from the listings is available at http://codentronix.com/2011/04/20/simulation-of-3d-point-rotation-with-python-and-pygame

References

Bakeman, R., & McArthur, D. (1996). Picturing repeated measures: Comments on Loftus, Morrison, and others. *Behavior Research Methods, Instruments, & Computers*, *28*, 584–589, https://doi.org/10.3758/BF03200546.

Bar, M., & Biederman, I. (1998). Subliminal visual priming. *Psychological Science*, *9*, 464–468, https://doi.org/10.1111/1467-9280.00086.

Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, *94*, 115–147, https://doi.org/10.1037/0033-295X.94.2.115.

Biederman, I., & Cooper, E. E. (1991). Evidence for complete translational and reflectional invariance in visual object priming. *Perception*, *20*, 585–593, https://doi.org/10.1068/p200585.

Biederman, I., & Cooper, E. E. (2009). Translational and reflectional priming invariance: A retrospective. *Perception*, *38*, 809–825, https://doi.org/10.1068/pmkbie.

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1162–1182, https://doi.org/10.1037/0096-1523.19.6.1162.

Biederman, I., & Ju, G. (1988). Surface versus edge-based determinants of visual recognition. *Cognitive Psychology*, *20*, 38–64, https://doi.org/doi/10.1016/0010-0285(88)90024-2.

Epstein, W., & Hatfield, G. (1978). Functional equivalence of masking and cue reduction in perception of shape at a slant. *Perception & Psychophysics*, *23*, 137–144, https://doi.org/10.3758/BF03208294.

Epstein, W., Hatfield, G., & Muise, G. (1977). Perceived shape at a slant as a function of processing time and processing load. *Journal of Experimental Psychology: Human Perception and Performance*, *3*, 473–483.

Epstein, W., & Lovitts, B. E. (1985). Automatic and attentional components in perception of shape-at-a-slant. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 355–366.

Fischler, M. A., & Bolles, R. C. (1981). Random sample consensus: A paradigm for model fitting with application to image analysis and automated cartography. *Communications of the ACM*, *24*, 381–395, https://doi.org/10.1145/358669.358692.

Fiser, J., & Biederman, I. (2001). Invariance of long-term visual priming to scale, reflection, translation, and hemisphere. *Vision Research*, *41*, 221–234, https://doi.org/10.1016/S0042-6989(00)00234-0.

Foster, D. H., Craven, B. J., & Sale, E. R. H. (1992). Immediate color constancy. *Ophthalmic and Physiological Optics*, *12*, 157–160, https://doi.org/10.1111/j.1475-1313.1992.tb00280.x.

Gibson, J. J. (1986). *The ecological approach to visual perception*. Hillsdale, NJ: Erlbaum.

Humphreys, G. W. (1983). Reference frames and shape perception. *Cognitive Psychology*, *15*, 151–196, https://doi.org/10.1016/0010-0285(83)90008-7.

Humphreys, G. W. (1984). Shape constancy: The effects of changing shape orientation and the effects of changing the position of focal features. *Perception & Psychophysics*, *36*, 50–64, https://doi.org/10.3758/BF03206353.

Humphreys, G. W., & Quinlan, P. T. (1987). Normal and pathological processes in visual object constancy. In G. W. Humphreys & M. J. Riddoch (Eds.), *Object processing: A cognitive neuropsychological approach* (pp. 43–105). Hillsdale, NJ: Erlbaum.

Humphreys, G. W., & Quinlan, P. T. (1988). Priming effects between two-dimensional shapes. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 203–220.

Huttenlocher, D. P., & Ullman, S. (1990). Recognizing solid objects by alignment with an image. *International Journal of Computer Vision*, *5*, 195–212, https://doi.org/10.1007/BF00054921.

JASP, Team. (2017). JASP (Version 0.8.1.0). Retrieved from https://jasp-stats.org/.

Kanade, T., & Kender, J. R. (1983). Mapping image properties in to shape constraints: Skewed symmetry, affine-transformable patterns, and the shape-from-texture paradigm. In J. Beck, B. Hope, & A. Rosenfeld (Eds.), *Human and machine vision* (pp. 237–257). New York, NY: Academic Press.

Leibowitz, H., & Bourne, L. E. (1956). Time and intensity as determiners of perceived shape. *Journal of Experimental Psychology*, *51*, 277–281.

Lowe, D. G. (1987). Three-dimensional object recognition from single two-dimensional images. *Artificial Intelligence*, *31*, 355–395, https://doi.org/10.1016/0004-3702(87)90070-1.

Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. San Francisco, CA: W. H. Freeman & Co.

Marr, D., & Nishihara, H. K. (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, *207*, 187–217, https://doi.org/10.1098/rspb.1978.0020.

McReynolds, D. P., & Lowe, D. G. (1996). Rigidity checking of 3D point correspondences under perspective projection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *18*, 1174–1185, https://doi.org/10.1109/34.546255.

Norman, L. J., Akins, K., Heywood, C. A., & Kentridge, R. W. (2014). Color constancy for an unseen surface. *Current Biology*, *24*, 2822–2826, https://doi.org/10.1016/j.cub.2014.10.009.

Peirce, J. W. (2007). PsychoPy—Psychophysics software in Python. *Journal of Neuroscience Methods*, *162*, 8–13, https://doi.org/10.1016/j.jneumeth.2006.11.017.

Plant, R., & Quinlan, P. T. (2013). Could millisecond timing errors in commonly used equipment be a cause of replication failure in some neuroscience studies? *Cognitive Affective Behavioral Neuroscience*, *13*, 598–614, https://doi.org/10.3758/s13415-013-0166-6.

Quinlan, P. T. (1991). Differing approaches to two-dimensional shape recognition. *Psychological Bulletin*, *109*, 224–241, https://doi.org/10.1037/0033-2909.109.2.224.

Quinlan, P. T. (1995). Evidence for the use of scene-based frames of reference in two-dimensional shape recognition. *Spatial Vision*, *9*, 101–125, https://doi.org/10.1163/156856895X00133.

Quinlan, P. T., & Humphreys, G. W. (1993). Perceptual frames of reference and two-dimensional shape recognition: Further examination of internal axes. *Perception*, *22*, 1343–1364, https://doi.org/10.1068/p221343.

Ro, T., Singhal, N. S., Breitmeyer, B. G., & Garcia, J. O. (2009). Unconscious processing of color and form in metacontrast masking. *Attention, Perception & Psychophysics*, *71*, 95–103, https://doi.org/10.3758/APP.71.1.95.

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. *Journal of Mathematical Psy-

chology, *56*, 356–374, https://doi.org/doi:10.1016/j.jmp.2012.08.001.

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review*, 417–447, https://doi.org/10.1037/0033-295X.91.4.417.

Shepard, R. N. (2001). Perceptual-cognitive universals as reflections of the world. *Behavioral and Brain Sciences*, *24*, 581–601. doi: https://doi.org/10.1017/S0140525X01000012.

Shepard, R. N., & Farrell, J. (1985). Representation of the orientations of shapes. *Acta Psychologica*, *59*, 103–121, https://doi.org/10.1016/0001-6918(85)90044-7.

Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2011). False-positive psychology: Undisclosed flexibility in data collection and analysis allows presenting anything as significant. *Psychological Science*, *22*, 1359–1366, https://doi.org/10.1177/0956797611417632.

Ullman, S. (1985). *The interpretation of visual motion*. Cambridge, MA: The MIT Press.

Ullman, S. (1989). Aligning pictorial descriptions: An approach to object recognition. *Cognition*, *32*, 193–254, https://doi.org/10.1016/0010-0277(89)90036-X.

Vuilleumier, P., Henson, R. N., Driver, J., & Dolan, R. J. (2002). Multiple levels of visual object constancy revealed by event-related fMRI of repetition priming. *Nature Neuroscience*, *5*, 491–499, https://doi.org/10.1038/nn839.

Warrington, E. K., & James, M. (1986). Visual object recognition in patients with right-hemisphere lesions: Axes or features? *Perception*, *15*, 355–366, https://doi.org/10.1068/p150355.

Wetzels, R., Matzke, D., Lee, M. D., Rouder, J. N., Iverson, G. J., & Wagenmakers, E.-J. (2011). Statistical evidence in experimental psychology: An empirical comparison using 855 t tests. *Perspectives in Psychological Science*, *6*, 291–298, https://doi.org/10.1177/1745691611406923.