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The role of convexity in perception of symmetry and in visual short-term memory

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Visual perception of shape is affected by coding of local convexities and concavities. For instance, a recent study reported that deviations from symmetry carried by convexities were easier to detect than deviations carried by concavities. We removed some confounds and extended this work from a detection of reflection of a contour (i.e., bilateral symmetry), to a detection of repetition of a contour (i.e., translational symmetry). We tested whether any convexity advantage is specific to bilateral symmetry in a two-interval (Experiment 1) and a single-interval (Experiment 2) detection task. In both, we found a convexity advantage only for repetition. When we removed the need to choose which region of the contour to monitor (Experiment 3) the effect disappeared. In a second series of studies, we again used shapes with multiple convex or concave features. Participants performed a change detection task in which only one of the features could change. We did not find any evidence that convexities are special in visual short-term memory, when the to-be-remembered features only changed shape (Experiment 4), when they changed shape and changed from concave to convex and vice versa (Experiment 5), or when these conditions were mixed (Experiment 6). We did find a small advantage for coding convexity as well as concavity over an isolated (and thus ambiguous) contour. The latter is consistent with the known effect of closure on processing of shape. We conclude that convexity plays a role in many perceptual tasks but that it does not have a basic encoding advantage over concavity.

Keywords: Convexity; Concavity; Visual short-term memory; Symmetry.

Interest in convexity as a factor in how shape is perceived dates back to Gestalt psychology (Arnheim, 1954; Kanizsa & Gerbino, 1976; Rubin, 1958). Convex regions of an image are perceived as foreground, even when convexity is pitted against other grouping factors such as symmetry or size (Kanizsa & Gerbino, 1976). Convexity also makes observers respond faster to the presence of a foreground region even when the shape of the foreground is irrelevant for the task (Bertamini & Lawson, 2006). Important analyses have highlighted the fact that concavities (and therefore convexities) along a contour may be the basis for perceived solid shape and part structure (Hoffman & Richards, 1984; Koenderink, 1984). Therefore many studies that have reported effects of convexity

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and concavity have tried to explain the empirical data in terms of how the visual system treats these aspects of a contour differently.

The empirical data do not fit a simple story; in particular both convexity and concavity advantages have been reported for different tasks. For instance, in relation to attention, a concavity advantage has been found using a change detection task (Barenholtz, Cohen, Feldman, & Singh, 2003) and the visual search paradigm (Hulleman, te Winkel, & Boselie, 2000; Humphreys & Müller, 2000). However, a convexity advantage has been reported in a task requiring a probe discrimination (Barenholtz & Feldman, 2003), a positional discrimination task (Bertamini, 2001; Bertamini & Farrant, 2006; Gibson, 1994), and detection of symmetry (Hulleman & Olivers, 2007). Other studies have reported no difference for convexity or concavity for some tasks such as change detection (Bertamini, 2008) or visual search (Bertamini & Lawson, 2006) when perceived part structure is unchanged between the two intervals or between the items of the search display. Finally, a recent study using an adaptation procedure near threshold found that after adapting to specific parts of a shape (concave maxima, convex maxima, inflections), each part generated a similar magnitude aftereffect (Bell, Hancock, Kingdom, & Peirce, 2010).

To shed new light on these issues, we report two series of studies. In the first, we tested perception of symmetry and repetition, using a methodology introduced by Hulleman and Olivers (2007). In particular we are interested in exploring the generality of this result because it is possible that this convexity advantage is specific to the task of comparing the opposite sides of a bilateral symmetric stimulus. If so, this would explain the absence of such advantage in other tasks. It has long been recognized that bilateral symmetry has a special role for visual perception (Bertamini, 2010; Mach, 1959).

In the second set of studies, we investigated visual short-term memory (VSTM) for contour regions perceived either as convex or as concave. These experiments specifically test how convexities and concavities are retained in memory. If convexities play a critical role in symmetry detection, we need to relate this to the question of sensitivity to convexities and concavities information in memory. Previous work has found a mixture of local and global effects (Cohen, Barenholtz, Singh, & Feldman, 2005; Vandekerckhove, Panis, & Wagemans, 2007). The interpretation of a contour as either convex or concave depends on its closure (Elder & Zucker, 1993). To establish whether convexity and concavity information itself is important for how shape is stored in VSTM, we included an unclosed contour condition in our second set of studies. We then try to draw conclusions based on the overall findings.

Detection of bilateral symmetry and repetition

In the first set of studies (Experiments 1–3), we explored in more depth a recently discovered convexity advantage. Hulleman and Olivers (2007) asked participants to report which of a pair of stimuli had perfect bilateral symmetry. The foil stimulus was similar to the symmetric stimulus but the deviations from perfect symmetry could be located either on the convex regions of the contour or in the concave regions. They found that it is easier to detect asymmetry when there is a mismatch between the convexities on either side of the symmetry axis, and they concluded that the concavities are less important than convexities in symmetry perception.

We modified the original stimuli to improve the way that convexities and concavities were matched. In particular, the stimuli used in Hulleman and Olivers (2007, see their Figure 2) contained a shape at the base of the object that was always a convexity. This could serve as a reference but no equivalent reference was present for concavity. In our stimuli, we made sure that the bottom and top of the stimuli were identical (Figure 1). This avoids the presence of the extra convexity in the stimuli that never changed in the original study and might have provided a visual reference for the participants.

Another minor change with respect to the original study is the fact that we used two levels of presentation time: 100 ms and 450 ms. In other words, for both the one-object and the two-objects conditions we have both short and long presentations. In the original study, presentation time was chosen to try and equate the level of performance. We expected that the difference in performance due to presentation time would be small given that, as in the original study, we did not include a mask after the presentation of the stimuli.

The main research question that we wanted to answer is whether the effect found by Hulleman and Olivers (2007) is specific to perception of bilateral symmetry. The visual system is highly efficient at detecting bilateral symmetry (Barlow & Reeves, 1979; Bruce & Morgan, 1975), and it is possible that the role of convexity reported by Hulleman and Olivers is specific to the task of matching two sides of a symmetric object. To this end, we used the same task in a separate experiment in which there was a repetition of two objects (see Figure 4, later) instead of a pair of symmetric objects (Figure 1).

EXPERIMENT 1A: SYMMETRY

Method

Participants

Thirty-two members of the University of Liverpool community took part in the study (6 male, 26 females) and received course credit for participation. Half were assigned to the 100-ms condition and half to the 450-ms condition. Half were tested first on the single-object condition and next on the two-objects condition and the other half in the reversed order.

Stimuli

Creation of the one-object stimuli followed the method used in Hulleman and Olivers (2007). Nine different convexities and concavities were generated by fitting Hermite polynomials to triads of points positioned on the edge of a rectangle of 40×30 pixels. The height of the

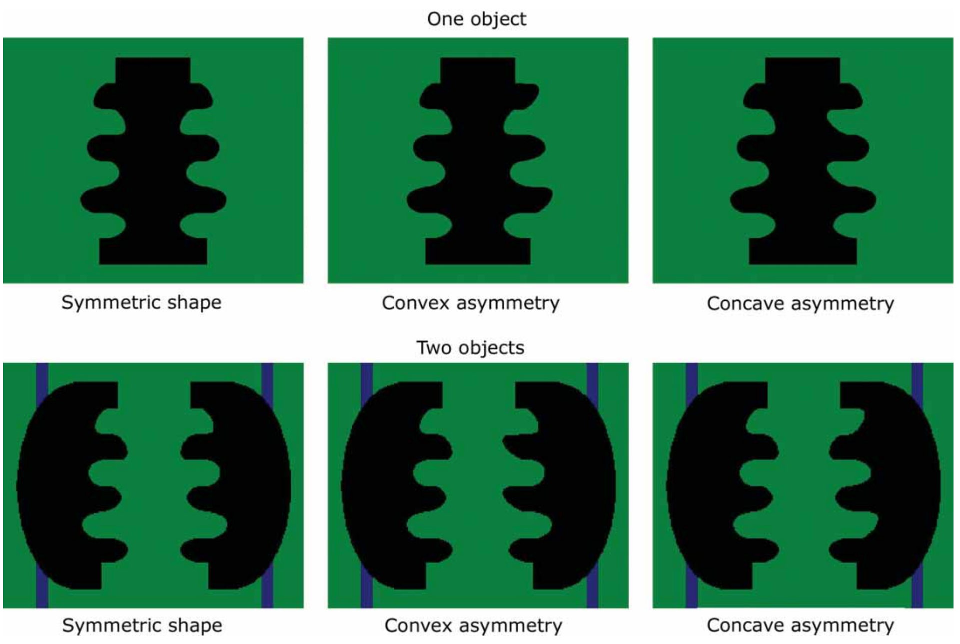

Figure 1. *Examples of stimuli used in Experiment 1a. Vertical blue bars were part of the background on which the two objects were presented. This was done to ensure that the black regions were seen as figures rather than ground. To view a colour version of this figure, please see the online issue of the Journal.*

convexities and concavities was always 40 pixels. Their shape was determined by the position of the third point along the side of the rectangle. This point could be either halfway or 5 pixels above or below the middle. Three concavities and convexities were chosen randomly from the nine and were concatenated vertically to form one half of the stimulus. For a symmetric stimulus, the side was mirrored. For an asymmetric stimulus, the side was mirrored too, but the point on the side of either all convexities or all concavities was shifted 9 pixels upward and 4 pixels closer to the centre. Both at the top and at the bottom of the resulting stimulus, a rectangle 40 pixels high was added to ensure that there was no reference point. The width of the rectangle was determined by the position of the endpoints of top and bottom convexities and concavities. The total height of the stimulus was 280 pixels, which corresponded to 7 cm on the monitor. The two-object stimuli were created by generating a one-object stimulus, inverting figure and ground, and adding an ellipse of 280 × 200 pixels to reduce the chance of figure–ground reversals. We also added two blue stripes (18 pixels wide) that were occluded by the objects to further discourage reversals (see Figures 1 and 2). The stimuli were presented on a Sony monitor (resolution 1,024 × 768 at 85 Hz) controlled by an Apple Macintosh computer. Presentation and storage of the data were controlled by a program written in C++ and OpenGL.

Procedure

Each observer sat in a dimly illuminated room at a distance of approximately 57 cm from the monitor. The observers were given instruction and shown examples of the stimuli before the experiment started. During a trial, the first stimulus was presented for 100 ms (450 ms for a different group of observers). After a blank interval of 750 ms, the second stimulus was presented for the same duration (Figure 2). A blank display prompted the participants to reply and remained visible until the participant had responded. An additional blank interval of 1,500 ms preceded the start of the next trial. The participant's task was to press the "/" key or the "z" key to indicate that the symmetric shape was in the first or in the second interval. Participants were instructed to guess if they were uncertain. Each experiment started with 20 practice trials, and afterwards the observer was allowed to ask questions or request more practice. In the experimental phase there were 264 trials. The trials were presented in rapid succession, but after each block of 88 trials a message appeared, and the observer was allowed time to rest. The start of the subsequent blocks was self-paced.

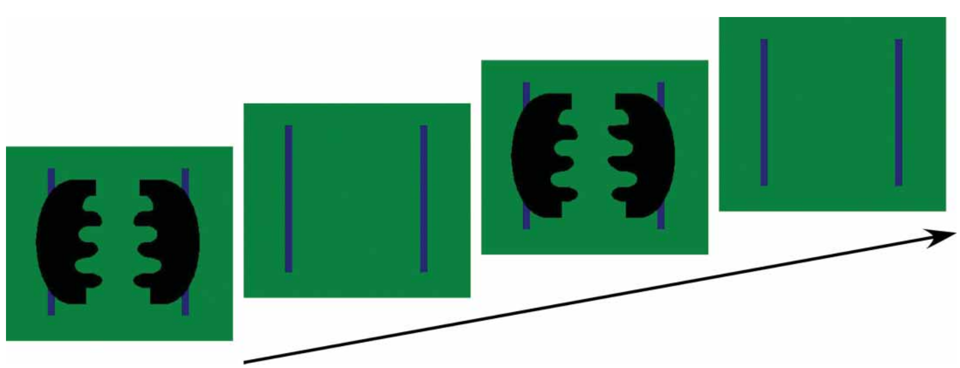

Figure 2. *In this example a asymmetric two-objects stimulus is shown in the first interval and an asymmetric stimulus is shown in the second interval. The concavities in this example are symmetric but the convexities are all different between the left and the right side. Note that the vertical blue bars were never removed so as to create a sense that the black objects overlap the blue ones. This reduces the chance of a figure–ground reversal. To view a colour version of this figure, please see the online issue of the Journal.*

Results

We performed a mixed analysis of variance (ANOVA) on percentage of correct data with convexity (mismatching convexities or concavities) and number (one or two objects) as within-subjects factors, order (one object first or second), and presentation time (100 and 450 ms) as a between-subjects factor. There was a significant effect of number, $F(1, 28) = 11.74$, $p = .002$, $\eta_p^2 = .29$, but no other significant effects or interactions (all ps $> .180$). As expected, the task was easier when a single object was present as opposed to a pair of objects. The difference in performance between short and long presentation time was small and nonsignificant. Much more surprisingly, we could not confirm an advantage of convexity over concavity as location of the mismatch. The graph of Figure 3 shows a trend in the same direction as the effect found by Hulleman and Olivers (2007) but our differences were much smaller. Although we report percentage correct so as to make the comparison with the original study more direct, we also performed a signal detection analysis on the data. An ANOVA with the same design as the one reported above, but using d' as the dependent variable, confirmed the same pattern. Specifically only the effect of number was significant, $F(1, 28) = 8.96$, $p = .006$, $\eta_p^2 = .24$.

EXPERIMENT 1B: TRANSLATION

In Experiment 1b, we used the same design as that for the two-objects condition of Experiment 1 except that we placed a pair of objects side by side (translation) instead of reflected around a symmetry axis. Therefore, the task was to compare the two objects and decide whether they were the same or different. We used 450 ms as presentation given that no significant difference had been detected in Experiment 1a.

Method

Participants

Sixteen members of the University of Liverpool community took part in the study (4 male, 12 females) and received course credit for participation.

Stimuli

The translated stimuli were generated starting with exactly the same procedure as that for the

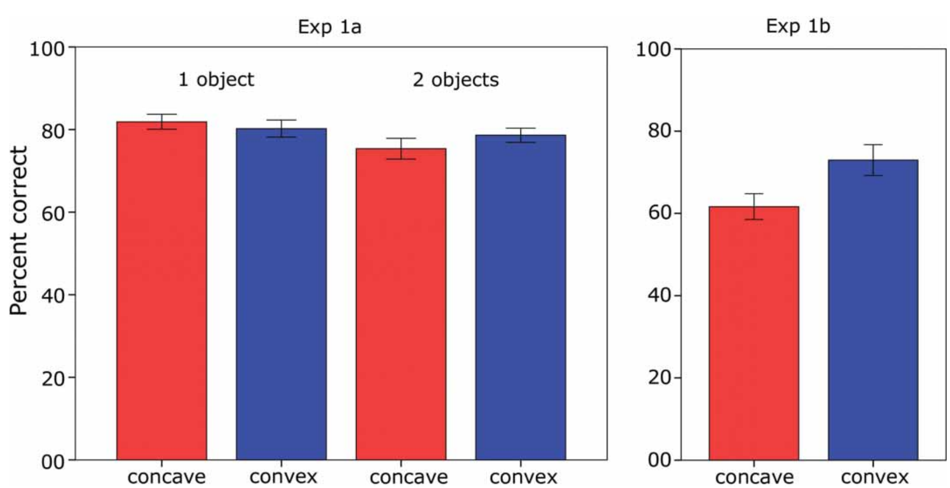

Figure 3. *Results for Experiment 1a (bilateral symmetry) and Experiment 1b (translation). Error bars are* ± 1 SEM. *Red (dark grey) bars: mismatch in concavities. Blue (light grey) bars: mismatch in convexities. To view a colour version of this figure, please see the online issue of the Journal.*

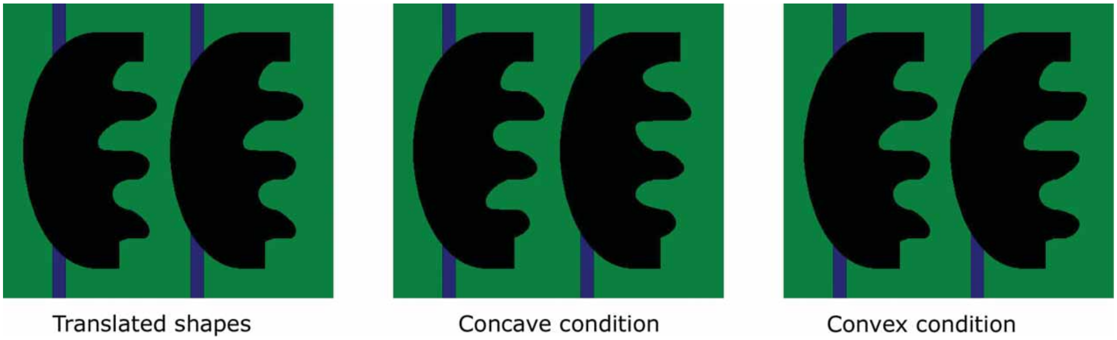

Figure 4. *Example stimuli used in Experiment 1b. Vertical blue bars were part of the background on which the two objects were presented. This was done to ensure that the black regions were seen as figures rather than ground. To view a colour version of this figure, please see the online issue of the Journal.*

symmetric stimuli. After each stimulus half was created, it was paired with a 280 × 100-pixel ellipse to complete the shape. This completed shape was then copied to create the two repeated shapes (Figure 4).

Procedure

The procedure and the stimuli for Experiment 1b were the same as those of Experiment 1a except that two objects were presented side by side instead of reflected around a symmetry axis (Figure 4). Presentation time was 450 ms. Observers pressed the "/" key or the "z" key to indicate whether the repeated pair of shapes was in the first or in the second interval.

Results

The mean percentage correct is shown in Figure 3. We analysed performance as in Experiment 1a but there was only one factor: convexity. The effect of convexity was significant, $F(1, 15) = 7.43$, $p = .015$, $\eta_p^2 = .33$, with higher performance for mismatches in convexities. An ANOVA with the same design as the one reported above, but using d' as the dependent variable, confirmed the same pattern. Specifically the effect of convexity was significant, $F(1, 15) = 7.17$, $p = .017$, $\eta_p^2 = .32$. This experiment therefore found a result similar to that of Hulleman and Olivers (2007) but using repeated instead of reflected shapes.

EXPERIMENT 2A: DETECTION OF SYMMETRY

In Experiment 1a, we failed to replicate the convexity advantage reported by Hulleman and Olivers (2007). However, the pattern of results did show a trend in the same direction. Moreover, we did find a convexity advantage in Experiment 1b, and it is therefore possible that Experiment 1a lacked power. In particular, the two-interval design of Experiment 1 allowed participants to base their answer either on the first or on the second interval. This opportunity to recover in the second interval from anything missed in the first might have reduced the power of Experiment 1 to detect a difference between convexities and concavities. A different design may improve sensitivity. We modified the procedure in the following way. In Experiment 2a we presented the stimuli in a single interval rather than two. We asked the participants to decide whether the stimulus was symmetric or not. We then analysed the results from this yes/no task on the basis of signal detection theory, to measure both sensitivity and bias.

Method

Participants

Sixteen members of the University of Liverpool community took part in the study (4 males, 12 females) and received course credit for participation.

Procedure

The procedure was similar to that of Experiment 1a. Observers were given instruction and were shown examples of the stimuli before the experiment started. The task was to press the "/" key when the stimulus was perceived as symmetric or the "z" key when it was seen as asymmetric. Presentation time was 450 ms. There was a practice phase of 20 trials and an experimental phase of 264 trials.

Results

The mean values for sensitivity and bias are shown in Figure 5. We performed a mixed ANOVA with convexity (mismatching convexities or concavities) and number (one or two objects) as within-subjects factors and order (one object first or second) as a between-subject factor. The dependent variable was d'. There was a significant effect of number, $F(1, 14) = 12.00$, $p = .004$, $\eta_p^2 = .46$, but no other significant effects or interactions (all ps $> .204$). Therefore, as expected, the task was easier when a single object was present as opposed to a pair of objects. We could not confirm an advantage of convexity over concavity, in line with the results of Experiment 1a.

We performed an ANOVA with the same design on a measure of bias (the standardized criterion c (Macmillan & Creelman, 1991). There was a significant effect of number, $F(1, 14) = 6.48$, $p = .023$, $\eta_p^2 = .32$, but no other significant effects or interactions (all ps $> .103$). There was a greater tendency to respond "yes" to a pair of objects than to a single object. Looking at the graph it appears that the pattern is for greater bias to respond yes in the conditions where sensitivity is lower. These differences, however, were relatively small.

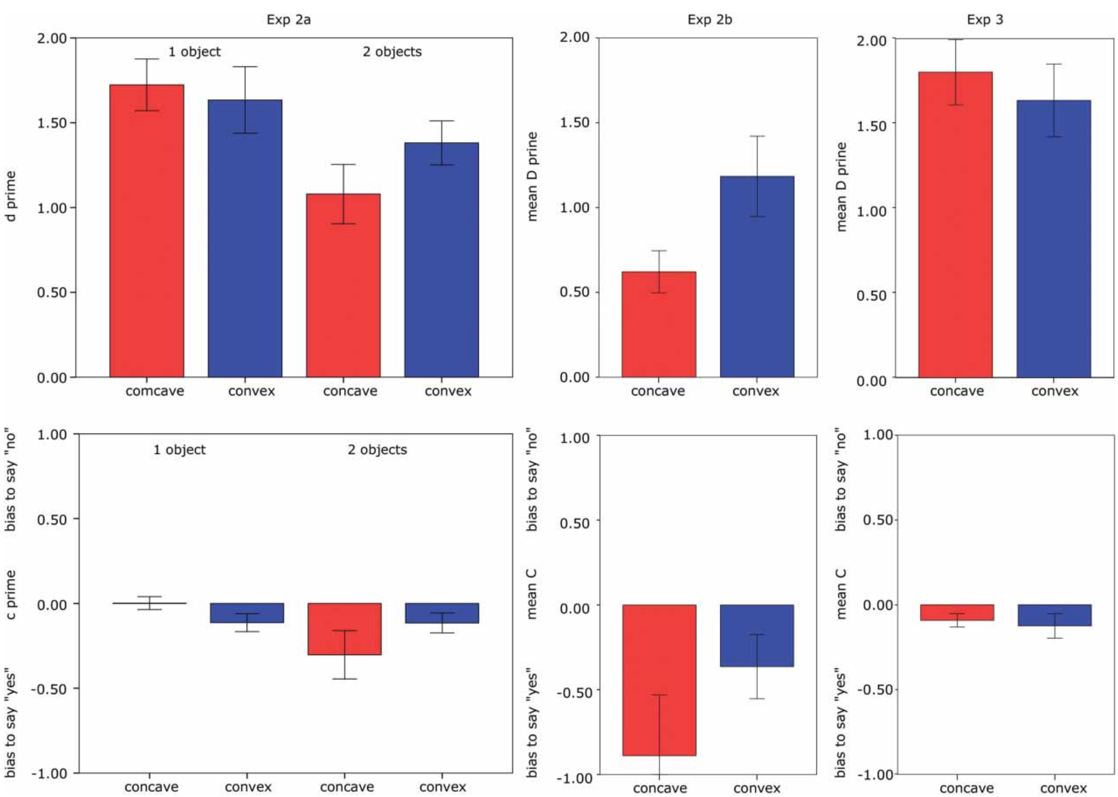

Figure 5. *Results from Experiment 2a (bilateral symmetry) and Experiments 2b and 3 (translation). Error bars are* ±*1* SEM. *Top row: sensitivity* (d′). *Bottom row: bias (c′). Red (dark grey) bars: mismatch in concavities. Blue (light grey) bars: mismatch in convexities.*

EXPERIMENT 2B: DETECTION OF TRANSLATION

Experiment 2b used the same design as that of Experiment 2a to test detection of translation instead of detection of bilateral symmetry.

Method

Participants

Sixteen members of the University of Liverpool community took part in the study (4 males, 12 females) and received course credit for participation.

Procedure

The same instruction and procedure as those in Experiment 1b were used, except in one point, that there was one interval rather than two intervals. The stimuli were the same as those used in Experiment 1a.

Results

The mean values for sensitivity and bias are shown in Figure 5. We analysed performance as in Experiment 2a but there was only one factor: convexity. This factor was significant for sensitivity, $F(1, 15) = 10.05$, $p = .006$, $\eta_p^2 = .40$, but not for bias. This result is consistent with the result of Experiment 1b: Performance is higher when the deviation for a perfect translation is located on the convexities. However, overall level of sensitivity for the concave condition was low, mean d' 0.62, and bias to say that the objects were the same was high, mean c value –0.89.

EXPERIMENT 3: COMPARING CONVEX AND CONCAVE AS SEPARATE TASKS

One the one hand, we have found a clear convexity advantage for the translated objects in both Experiment 1b and Experiment 2b. However, we found hardly any evidence for a convexity advantage in symmetry detection. In the one-object conditions of Experiment 1a and 1b, the mean scores for a mismatch in the concavities are actually higher. It is possible that methodological differences can explain the fact that we did not replicate the results of Hulleman and Olivers (2007) in our symmetry experiments. In particular, our stimuli did not include a reference convex part in the lower region of the objects. This might have moved participants away from a strategy where they concentrate on the convex parts. In this context, it is interesting to note that the stimuli that are best matched for the amount of convexity and concavity (one-object symmetric) are also the ones where the differences between convex and concave mismatches are smallest. But if more convexity in the stimulus is indeed guiding the participants towards a strategy that focuses on the convexities, this would offer an alternative explanation for the consistent convexity advantage in the translated condition. Here, both stimuli are overwhelmingly convex. So, it is therefore possible that the stimuli used in our experiments, and potentially also in the original results from Hulleman and Olivers (2007), may have guided the participants towards which part of the stimuli to monitor. To test this, we separated the two tasks. We asked observers to detect deviations from regularities carried by convexities in one set of trials and carried by concavities in another set of trials. Because of this change, observers were no longer faced with a choice about which region of the stimuli to assign priority while they were monitoring shape information. We would therefore expect that the convexity advantage for translation will disappear.

Method

Participants

Sixteen members of the University of Liverpool community took part in the study (2 males, 14 females) and received course credit for participation.

Procedure

The procedure was the same as that in Experiment 2b. Half of the participants were tested on the convex condition first and next on the concave condition, and the other half were tested in the reversed order.

Results

The mean values for sensitivity and bias are shown in Figure 5. We analysed performance as in Experiment 2b, with the added factor of order (convexity first or concavity first). Convexity was not significant for either sensitivity or bias. In addition there were no other significant effects or interactions.

For sensitivity, the level of performance was much higher than that in Experiment 2b, and if anything the trend was for a higher mean in the concave condition, thus showing a complete change in pattern with respect to Experiment 2b. This was confirmed by an ANOVA in which we entered both experiments. The version of the experiment was significant, $F(1, 30) = 10.63$, $p = .002$, $\eta_p^2 = .27$, and there was an interaction between version and convexity, $F(1, 30) = 8.08$, $p = .008$, $\eta_p^2 = .21$.

Taking these results together, we conclude that when observers are faced with a difficult task in which perfect performance is impossible, they may orient their attention towards convexities. This is a type of strategic choice, and it is likely to have been the case also in Hulleman and Olivers (2007). However, a more direct comparison between performance for detection of irregularities within convexities and within concavities does not confirm any basic different in sensitivity.

Visual short-term memory

In our first set of experiments (1a, 1b, 2a, and 2b), we found that in the translation task participants may direct their attention preferentially towards convexities. The fact that this difference was driven by a strategy rather than a basic difference in sensitivity was supported by the results of Experiment 3.

In the literature, there have been some claims that the detection of a change in a concavity is easier than the detection to a change in a convexity (Barenholtz et al., 2003). Barenholtz et al. conclude that this may have been due to either a specific advantage for concavity or an indirect effect due to changes in perceived part structure, which Vandekerckhove et al. (2007) call local and global factors. In another paper, Cohen et al. (2005) argue in favour of the first interpretation—that is, a basic advantage for processing concavities. However, Bertamini (2008) has argued that all the evidence is consistent with the fact that detection is easier only when part structure changes, and this is exactly what happens whenever a region is changed from convex to concave or vice versa. But Bertamini found no difference in a direct comparison of changes to a convex vertex compared to a concave vertex, and within a convex region compared to a concave region (Bertamini, 2008). In our second set of studies, we used stimuli similar to those used in Experiments 1 and 2, but the task was more similar to that used in Bertamini (2008) and in Cohen et al. (2005). However, we increased the retention interval to 1 s, to be more consistent with the classic paradigm used to study visual short-term memory (Luck & Vogel, 1997). We also used a set of 3 or 4 features to be remembered, because this is considered the limit of short-term memory (Cowan, 2001). It is possible that having to perform at the limit of the short-term memory capacity will reveal a difference between convexities and concavities that may not be present for tasks with fewer features and shorter retention intervals.

EXPERIMENT 4: MEMORY FOR CONVEXITIES AND CONCAVITIES

In Experiment 4, we presented a contour that was shaped so as to form a series of features, as shown in Figure 6. For one group of participants there were three features, and for another there were four features. These features were selected from a set of four different contour shapes, and the only constraint was that they could never be all the same within one stimulus. The stimuli thus generated therefore belonged to a large population of possible combinations of four (or three for the other group) ordered items selected from a set of four shapes with replacement.

For a given participant, the features to memorize were always located either on the left or on the right side of a chain of shapes. The shapes on the opposite side were more rectangular and therefore different from any of the shapes used to generate the relevant features. In the example of Figure 6, the features to retain in memory are on the left side. On the right side the contour has four identical shapes that never change throughout the experiment. Closure of the contour generated the convex and concave conditions. Therefore, although the contour was always located in the same spatial location on the screen, closure to the right or to the left meant that the features were perceived as either convex or concave. For half of the participants, the left–right orientation of the stimuli was reversed. This way, participants were always able to predict the location of the stimuli that they had to retain in memory. The aim of the study was to compare changes in convexities to changes in concavities to determine which of the two are more easily retained in VSTM.

Method

Participants

Forty members of the University of Liverpool community took part in the study (9 males, 31 females) and received course credit for participation.

Design and stimuli

There were three interleaved conditions: baseline, convex features, and concave features. Half of the participants were assigned to the four-features condition and half to the three-features condition. Within each condition, for half of the participants

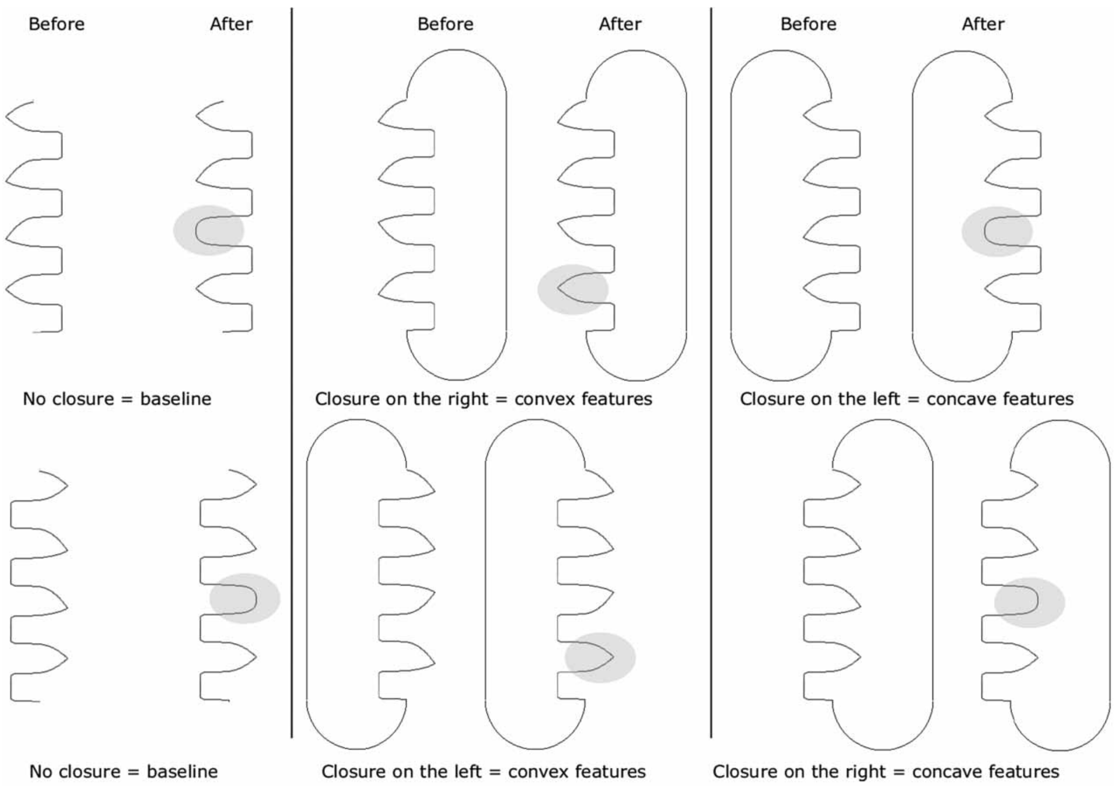

Figure 6. *Example of stimuli used in Experiment 4. The contour with four features was presented in a fixed position throughout a session. For some observers, the features were on the left (top row), and for others they were on the right (bottom row). Without closure (baseline condition) the convexity or concavity of the contour was ambiguous. In the convex condition, a curved contour provided closure on one side, and in the concave condition the contour provided closure on the other side. The feature that changed between intervals in these examples is highlighted. Note that without closure all three conditions would be identical. This observation underlines the fact that closure is task irrelevant.*

the features to be monitored were on the right of the features that did not change, and for the other half they were on the left. On a trial-by-trial basis, stimuli were created by selecting at random one shape for each position from a set of four possible shapes. These shapes were then connected to form features, with the only constraint that all shapes could not be the same. This constraint was present for each of the two intervals.

Procedure

Each observer sat in a dimly illuminated room at a distance of approximately 57 cm from the monitor. The observers were given instruction and were shown examples of the stimuli before the experiment started. They were instructed to press the "z" key on the keyboard if the features did not change between intervals and to press the "/" key if one of the features did change. After a practice phase with 24 trials, each participant performed 144 trials divided in three blocks of 48 trials each. The trials were presented in rapid succession, but at the end of a block the observer was allowed time to rest. The start of the subsequent block was self-paced. Each trial consisted of a first presentation lasting 1.6 s. This presentation was followed by a 1-s blank screen and by the second presentation, which remained on the screen until a response was produced.

Results

Mean sensitivity (d') and mean bias (c') are shown in Figure 7. A mixed ANOVA on d' included condition (baseline, convex, and concave) as a within-subjects factor, and number of features (three and four) and position (left or right) as between-subjects factors. In order to specifically test convexity, we included a contrast that compared just convexity and concavity levels, and to test closure, we included a contrast that compared baseline (open) to the average of the other two conditions (closed). There were no significant main effects, and the contrast comparing convexity and concavity was also not significant, $F(1, 36) = 0.16$. However, the contrast that tested the effect of closure was significant, $F(1, 36) = 4.71$, $p = .037$, $\eta_p^2 = .12$. Performance was better for closed shapes than it was in the baseline condition. This is consistent with the literature because closure is a factor that enhances shape detection (Elder & Zucker, 1993) and modulates shape adaptation (Bell et al., 2010).

The same analyses as those performed on d' were also performed on a measure of bias. We used the standardized c criterion. The size of the bias was small, and there were no significant effects or interactions (all ps $> .197$).

EXPERIMENT 5: MEMORY FOR FEATURES WITH A CHANGE IN CONVEXITIES AND CONCAVITIES

In Experiment 4, we found that detection of changes to convex or concave features did not differ but detection of changes to features that were either convex or concave was better than detection of changes to the baseline open contour. There are two explanations for this result. Both of them are based on our suggestion that this is evidence for the role of closure in enhancing shape processing. One possible mechanism is that the surface of the closed objects helped in confining the spreading of attention to a small region of space. Another possibility is that because the contour in the baseline condition was ambiguous with respect to convexity and concavity, the interpretation may have changed from one interval to the next, thus leading to the perception of a change when there was no change. Although this second interpretation would predict an increase in the bias in the negative direction (to respond different), there was no evidence of this. Nevertheless the ambiguity may have contributed to making the task harder.

Experiment 5 was similar to Experiment 4, but the way that the contours closed to form an object changed from the first to the second interval. Therefore, observers saw convex features in the first interval but had to judge the change after seeing concave features in the second interval (or vice versa). Note that the location of the stimuli to remember was still fixed for each participant as in Experiment 4. If the advantage found in Experiment 4 was strictly

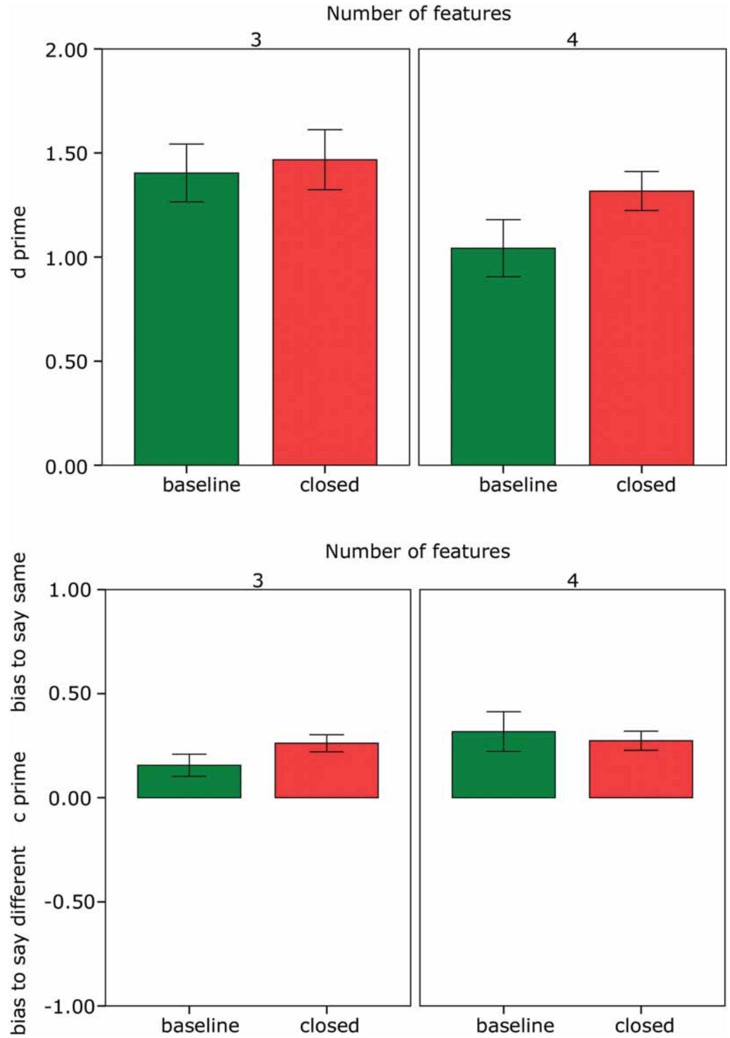

Figure 7. *Results from Experiment 4. The closed condition includes both convex and concave stimuli because there was no significant difference between these two. Error bars are ±1* SEM*. To view a colour version of this figure, please see the online issue of the Journal.*

a consequence of closure and the fact that the closed objects are confined surfaces, then the advantage should be replicated in Experiment 5. However, if the coding of convexity and concavity matters, then the change between intervals should destroy the closure advantage. Finally, if the convexity switch was the cause of the relative poor performance in the baseline condition—that is, if there was a 50% chance for what initially was perceived as convex to be subsequently perceived as concave or vice versa—then in Experiment 5 the closed conditions may lead to worse performance than baseline, because there should also be a 50% chance of coding to remain the same in the baseline condition.

Method

Participants

Forty members of the University of Liverpool community took part in the study (10 males, 30 females) and received course credit for participation. Half were assigned to the four-features condition and half to the three-features condition.

Design

There were three interleaved conditions: baseline, change from convex to concave, and change from concave to convex. Half of the participants were assigned to the four-features condition and half to the three-features condition. Within each condition, for half of the participants the features to be monitored were on the right of the features that did not change, and for the other half they were on the left.

Procedure

The procedure was the same as that of Experiment 4. Observers were asked to compare a stimulus before and after a 1-s retention interval and to judge whether the shape was the same or not. After 24 practice trials, each participant performed 144 experimental trials. Unlike Experiment 4, closure was always changed between the two intervals creating the convex → concave condition and the concave → convex condition.

Results

Mean sensitivity (d') and mean bias (c') are shown in Figure 8. A mixed ANOVA on d' included condition (baseline, convex → concave, and concave → convex) as a within-subjects factor, and number of features (three and four) and position (left or right) as between-subjects factors. In order to specifically test direction of change, we included a contrast that compared convex → concave and concave → convex, and to test closure we included a contrast that compared baseline (open) to the average of the other two conditions (closed). There was a significant main effect of condition, $F(2, 36) = 5.05$, $p = .009$, $\eta_p^2 = .12$, and a significant interaction between number of parts and position, $F(1, 36) = 4.79$, $p = .035$, $\eta_p^2 = .12$. The contrast comparing direction of change was significant, $F(1, 36) = 5.69$, $p = .022$, $\eta_p^2 = .14$: The change from convex to concave was easier to detect than vice versa. Finally, the contrast that tested the effect of closure was significant, $F(1, 36) = 4.47$, $p = .042$, $\eta_p^2 = .11$: Performance was better for the baseline shapes than it was in the closed conditions.

The same analyses as those performed on d' were also performed on a measure of bias. We used the standardized c criterion. There was a main effect of condition, $F(2, 36) = 5.17$, $p = .008$, $\eta_p^2 = .13$, and a significant interaction between number of parts and position, $F(1, 36) = 6.72$, $p = .014$, $\eta_p^2 = .16$. There was also a significant effect of closure, $F(1, 36) = 16.73$, $p < .001$, $\eta_p^2 = .32$. There was a stronger tendency to say "same" in the baseline condition than when the convexity changed between intervals.

The advantage for the closed condition compared to baseline that was found in Experiment 4 reversed to a cost for the closed condition in Experiment 5. As discussed in the introduction of Experiment 5, this pattern of results suggests that convexity and concavity information is important for how shape is stored in VSTM. When observers have to remember convex or concave features, they perform better when they have to remember an ambiguous shape (open) than features that change between convex to concave or vice versa. Therefore the task is not carried out on the shape of open contours, but rather on contours whose curvature sign has already been extracted.

The large change in position of the object in Experiment 5 could be one of the causes in the lower performance. However, we note a few things. First, the first interval is identical in Experiments 4 and 5, so the change in location of the object is only a feature of the second interval, and in this interval the stimulus is only removed after the participants' response. Second, the closure of the object is entirely task irrelevant. Observers know this and learn about this aspect of the task during the practice. Third, the bias to respond same was actually stronger in Experiment 5 than in Experiment 4, suggesting that observers do not confuse a change in object position with the change in shape that they are asked to report.

Finally, the fact that detection performance was better for changes from convex to concave than vice versa might seem at odds with what we have argued

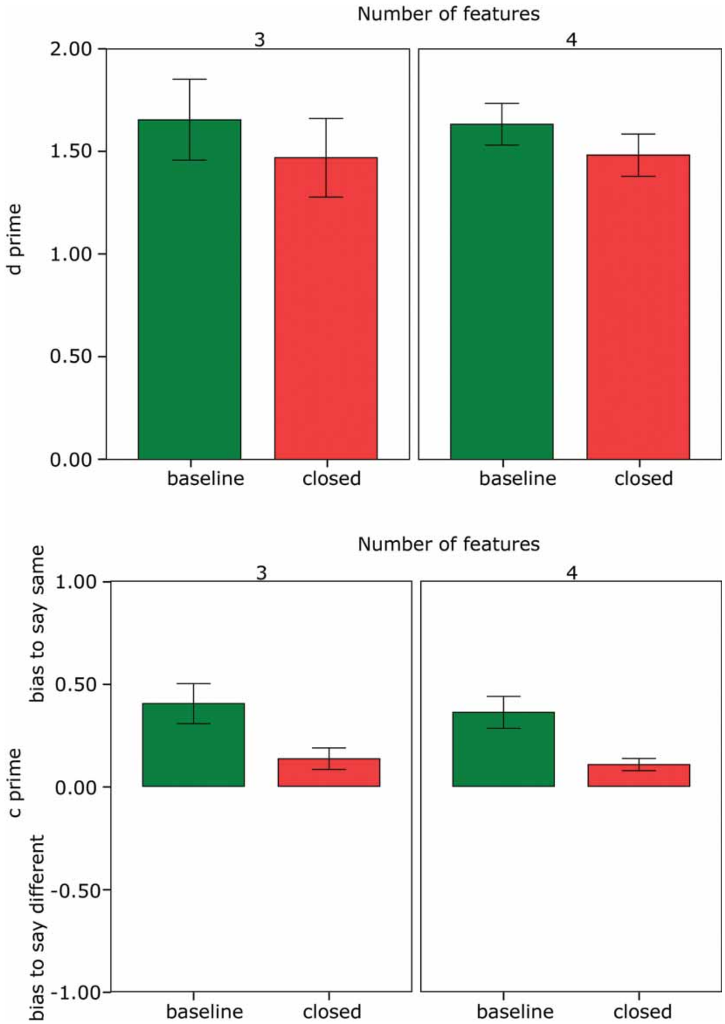

Figure 8. *Results from Experiment 5. Error bars are* ±*1* SEM*. To view a colour version of this figure, please see the online issue of the Journal.*

so far about a lack of difference when convexity and concavity are compared directly. However, as we have seen in the experiments on detection of symmetry and repetition, a convexity advantage might be found due to strategic choices made by the participants. If the participants were preferentially monitoring the convexities, they would become less sensitive to changes from concave to convex, because they are attending to the wrong part of the stimulus.

EXPERIMENT 6: CHANGE IN CONVEXITIES AND CONCAVITIES VERSUS NO CHANGE

We argued that the relative change in performance for the baseline condition in Experiments 4 and 5 reflects the fact that features coded as parts, either convexities or concavities, are easier to remember than an open segment of contour. However, this logic would predict that the overall level of performance in the baseline condition should be approximately the same in the two experiments. This did not seem the case from the graphs. We did not perform a direct statistical comparison because we believe that little can be gained from this between-subjects comparison, and we prefer to focus only on the within-subjects effects. The reason is the large individual variability that was present in all our experiments. To solve this problem, we conducted an extra control experiment in which we included both trials in which closure changed from left to right or vice versa and trials in which closure did not change. Experiment 6 is therefore a combination of Experiments 4 and 5. To prevent the number of trials from becoming prohibitively large, we only tested stimuli with four features.

Method

Participants

Twenty members of the University of Liverpool community took part in the study (8 males, 12 females) and received course credit for participation.

Design

There were five interleaved conditions: baseline, convex features, concave features, change from convex to concave, and change from concave to convex. For half of the participants, the features to be monitored were on the right of the features that did not change, and for the other half they were on the left.

Procedure

The procedure was the same as that of Experiment 5. After 24 practice trials, each participant performed 160 experimental trials.

Results

Mean sensitivity (d') and mean bias (c') are shown in Figure 9. A mixed ANOVA on d' included condition (baseline, same, and different) as a within-subjects factor and position (left or right) as a between-subjects factor. In order to specifically test the role of change in convexity and concavity, we included a contrast that compared the condition in which convexity changed (different) to the condition in which convexity remained the same (same), and to test closure we included a contrast that compared baseline (open) to the average of the other two conditions (closed). There was a significant main effect of condition, $F(2, 36) = 3.71$, $p = .034$, $\eta_p^2 = .17$. The contrast comparing change and no change was significant, $F(1, 18) = 7.86$, $p = .012$, $\eta_p^2 = .30$: Sensitivity was higher when the features remained the same in terms of convexity or concavity than when the features changed between intervals. However, the contrast that tested the effect of closure was not significant, $F(1, 18) = 0.01$, $p = .923$. So, closure did not in itself affect performance.

The same analyses as those performed on d' were also performed on a measure of bias (standardized c). There was a significant main effect of condition, $F(2, 36) = 10.23$, $p < .001$, $\eta_p^2 = .36$. The contrast comparing change and no change in convexity was significant, $F(1, 18) = 11.46$, $p = .003$, partial $\eta_p^2 = .38$: There was a stronger tendency to say "same" in the condition when the convexities did not change into concavities (or vice versa) between intervals. However, the contrast that tested the effect of closure was not significant, $F(1, 18) = 2.77$, $p = .113$.

The graph in Figure 9 shows that the baseline condition sits between the condition without a change of closure and the condition with a change of closure. This provides a valuable nuance to our interpretation of Experiment 5. Observers are able use the outline of the features to perform the task, as becomes clear from the lack of difference between performance in the outline condition and the closure conditions. However, coding the outline as either convex or concave improves performance. This is shown by the better performance when the convexities and concavities do not change from the first to the second interval. So, even though the sign of the curvature is irrelevant for the task, it is used to improve performance.

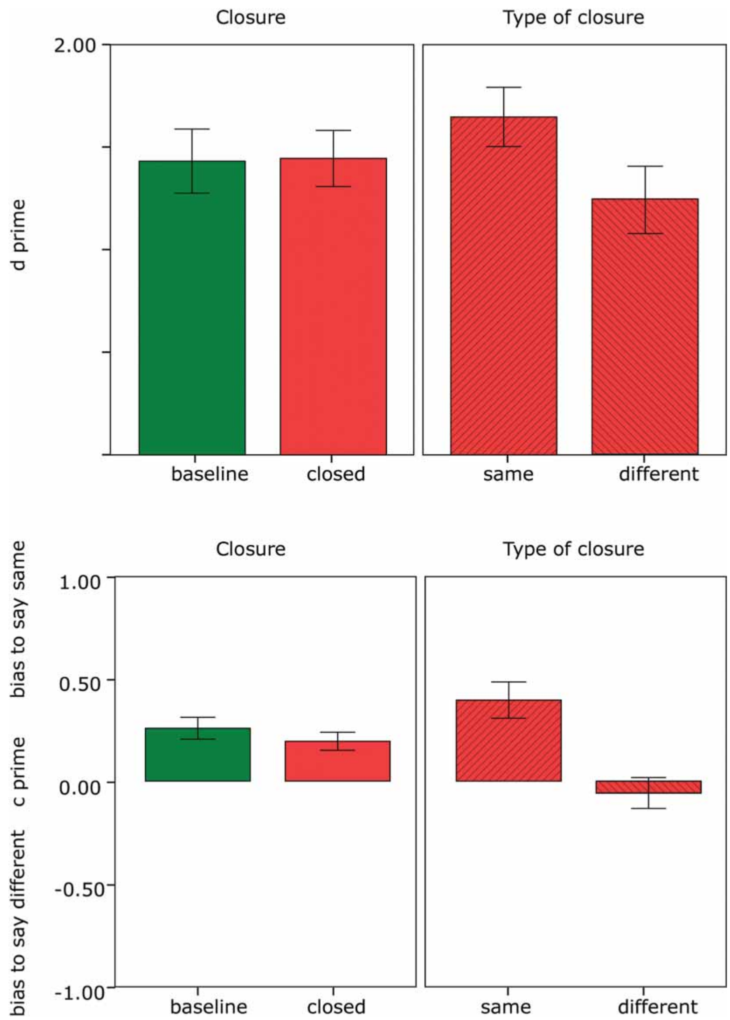

Figure 9. *Results from Experiment 6. Error bars are* ± 1 SEM. *To view a colour version of this figure, please see the online issue of the Journal.*

CONCLUSIONS

In two series of studies, we have explored perception of simple shapes and specifically the differences between convexities and concavities along a contour. The first set of experiments found an advantage for changes in convexities over changes in concavities in a task that required a comparison between two similar objects. Hulleman and Olivers (2007) also reported an advantage for changes in convexities. However, they found an advantage for comparing the left and right side of symmetric patterns (either within one object or across two objects). In our data, the effect for bilateral symmetry was not significant (Experiments 1a and 2a). The effect was only present for comparing features of translated objects, a condition that Hulleman and Olivers did not test (Experiments 1b and 2b).

There were some methodological differences between our experiments and Hulleman and Olivers's (2007). We were careful to create a situation in which convexity and concavity were as balanced as possible. Specifically, there was no difference in the total number of features that were perceived as convex and as concave in each stimulus. Results were consistent across two different procedures (a two-interval forced choice, as in the original study, and a single-interval detection task) and two measures of performance (percentage correct and d').

To explain our findings and the discrepancy with Hulleman and Olivers (2007), we asked the question whether participants had a tendency to monitor convexities and whether this strategy was the reason for the convexity advantage. To test this idea, we replicated the experiment in which we had found a clear convexity advantage (Experiment 2b) but we separated the task into two blocks (Experiment 3). In one block, participants had to detect a deviation from a perfect translation located at convexities, and in the other they had to detect deviations located at concavities. This simple modification completely changed the results, eliminating any sign of a convexity advantage. Therefore, we conclude that convexities are special only in that participants may strategically deploy more attention towards them when they are confronted with a difficult task in which it is impossible to monitor everything. We believe that this pattern is consistent with the literature. Convexities tend to be perceived as the important features of an object (e.g., Koenderink, 1990), but this does not imply any basic difference in terms of visual processing or sensitivity.

To further test for possible differences between convexity and concavities, in our second series of experiments we used a memory task. Observers had to remember contour segments that formed features along a single contour. This contour in some cases was closed to form an object. Closure also specified whether the features were perceived as convex or concave. Half of the time there was a change between the first and the second interval in one of the features. We tested stimuli with three or four features to engage VSTM with a task near the limits of its capacity. Again, we did not find any advantage for convexities over concavities. However, we did find an effect of closure.

In the literature there is empirical evidence for a difference between convexities and concavities in various tasks, but interpretation of these findings is controversial. Several perceptual tasks are sensitive to convexity or concavity coding, presumably because this type of coding plays a fundamental role in part parsing (Bertamini & Croucher, 2003; Hulleman et al., 2000). With respect to the narrower question of differences in detection, Barenholtz et al. (2003) and, more specifically, Cohen et al. (2005) have argued that detection performance for changes in concavities is higher than that for changes in convexities. However, Bertamini (2008) has argued that when convex and concave conditions are carefully matched there is no difference in sensitivity. We would argue that our current experiments provide further support for Bertamini's position.

This is in concordance with models of shape analysis and representation in the brain that utilize convexity and concavity information, but without assigning priority to one of them (Bell, Gheorghiu, & Kingdom, 2009; Connor, 2004). Suzuki (Suzuki, 2003; Suzuki & Cavanagh, 1998) has reported evidence of coding of convexity in inferotemporal areas. The convexity after-effect that Suzuki found is actually both a convexity and a concavity effect. However, one recent imaging study has reported a convexity advantage using a functional magnetic resonance imaging (fMRI) adaptation procedure (Haushofer, Baker, Livingstone, & Kanwisher, 2008). More imaging work on this topic is necessary.

Throughout this manuscript we have discussed 2D convexities and concavities. So, our results are not at odds with the convexity assumption in 3D shape perception (Hill & Bruce 1993; Johnston, Hill, & Carman, 1992; Langer & Bülthoff, 2001). From an ecological standpoint, an assumption of 3D convexity is logical as convex objects are more common than concave objects. However, convex and concave objects should not be equated to convexities and concavities in 2D because of how concave contours are in general projections of saddle regions on a surface and not projections of a concave surface (Koenderink, 1984).

With respect to the role of closure, there is good evidence that closure may facilitate shape processing (Elder & Zucker, 1993) including detection of change along a contour (Bell et al., 2010). If so, closed regions should be associated with better performance than a contour in isolation (not closed). We included this as a baseline condition in our experiments, and in Experiment 4 we found that change detection was better for closed objects than for the baseline. Closure may have acted to create parts that were easier to store in visual short-term memory but an alternative possibility is that closure simply allowed attention to remain constrained to a smaller region. In Experiment 5, we found that the closure advantage disappeared if the region changed from the left to the right side between intervals, thus changing convexities into concavities and vice versa. Experiment 6 confirmed the importance of closure using a within-subject design. We suggest that convexity and concavity are therefore important aspects of shape analysis and representation, but that there is no basic difference in sensitivity to changes to convexities and concavities.

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