The time course of figure-ground reversal

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We report the results from five experiments employing a modified version of the short-term visual matching (STVM) method introduced by Driver and Baylis (1996). In STVM, participants see a study display with ambiguous figure-ground relations. After the study display, participants have to decide which of two shapes in a match display was seen before in the study display. STVM has been used by Vecera, Vogel, and Woodman (2002) to demonstrate that the lower region is a figure-ground cue. In our modified version of STVM, the study stimulus was preceded by a brief prime. This caused a biasing of the figural interpretation of the ambiguous figure-ground displays that contained the lower region cue. We show that 100-msec priming with an unambiguous display is enough to affect the subsequent interpretation of the ambiguous figure-ground display. It takes maximally 350 msec to complete a transition from the nondominant interpretation to the dominant interpretation of an ambiguous figure-ground display that contains the lower region cue.

Ever since Rubin discussed the different interpretations of his famous face-vase stimulus in 1917, there has been considerable interest in figure-ground organization and its consequences. Several cues have been identified that influence the probability that a certain area of a stimulus will become organized as a figure. Palmer (1999) listed the following cues: surroundedness, size, orientation, contrast, symmetry, convexity, and parallelism. Peterson and Gibson (1994) provided evidence for a role of object memory in figure-ground assignment, with objects being more likely to be organized as figure than nonobjects. Recently, some new figure-ground cues have been described. Vecera, Vogel, and Woodman (2002) reported the lower region as a cue, Pinna, Werner, and Spillmann (2003) found that the "watercolor" effect influenced figure-ground organization, and Hulleman and Humphreys (2004) reported that top-bottom polarity biased the assignment of figure and ground.

Several pieces of evidence indicate that figure-ground organization is not totally immune to top-down influences. For instance, Girgus, Rock, and Egatz (1977) demonstrated that only half of their participants showed spontaneous reversals of an ambiguous face-vase stimulus. However, after they had been informed about the reversible nature of the face-vase stimulus, all of the participants showed reversals. More recently, Strüber and Stadler (1999) showed that when participants knew about the reversibility of a face-vase stimulus, they were capable of increasing and decreasing the number of reversals, if instructed to do so. Even though reporting reversals might be different from reporting which part of an ambiguous display is seen as a figure, these two results in-

dicate a considerable amount of top-down control over the assignment of figure and ground in ambiguous displays. Instructions about figure-ground organization and its reversible nature seem to be an obligatory part of experiments that use explicit reporting of which region is figure and which region is ground in a display (e.g., Peterson & Gibson, 1994; Pinna et al., 2003; Strüber & Stadler, 1999; Vecera et al., 2002).

Recently, implicit methods have been added to the explicit reporting tasks. In implicit methods, participants do not directly report which part of an ambiguous figure-ground display they perceive as figure. Rather, they are engaged in a task that depends on the figure-ground assignment of the ambiguous display. The short-term visual matching (STVM) method, introduced by Driver and Baylis (1996), has perhaps been the most influential of the implicit methods. In STVM, a figure-ground display is used as a study stimulus (see Figure 1A). Following a blank interval, participants have to decide which of two shapes in a match display was previously presented in the study display. This decision is made easier when the match display contains a shape that was organized as figure during the study phase. The STVM method is predicated on the assumption that edges are assigned to figural regions in displays. So when participants see a figure-ground display, one part will receive a figure description complete with a bounding edge, whereas the other part will only receive a (shapeless) ground description, without the bounding edge. When participants subsequently have to judge which of the two shapes in a match display was seen before, they should show a reaction time (RT) advantage¹ if the target shape was previously coded as figure in the study display. Baylis and Cale (2001) have shown that a figural region will only prime itself and not its (complementary) ground.

In the STVM method, there is an inverse relationship between figure-ground ambiguity and the size of the matching advantage. For totally ambiguous displays, ei-

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Figure 1. (A) Short-term visual matching. Following a fixation dot, an ambiguous figure–ground study display is presented. Following a blank screen, the participants have to match one of the two shapes of the match display with the ambiguous display. This sequence of displays was used in Experiment 1. (B) Primed short-term visual matching. Following the fixation dot, a priming display is inserted. The priming display will bias the interpretation of the subsequent study display. This sequence of displays was used in Experiments 2–4. The trial depicted is an upper region prime, upper region match trial. (C) The sequence of displays used in Experiment 5.

ther region of the ambiguous display will be seen as figure and confer a matching advantage on just half the occasions. In contrast, if the figure–ground relations are unambiguous, due to the presence of a clear figure–ground cue, there will be a consistent matching advantage for the part coded as figure.

In the present article, we have extended the STVM method to make it even more versatile. In our adaptation of this method, we inserted a priming display before the study display (the primed STVM procedure [PSTVM]; see Figure 1B). The priming display contained one of the two regions of the ambiguous figure–ground study display. The idea is that the region presented in the priming display will receive a figural interpretation, because it is the only shape on the screen, surrounded by a very large background. When the ambiguous display does not contain a strong figure–ground cue, the region that has been primed will probably hold onto its figural interpretation in the ambiguous display because no figure–ground information is available to challenge it. Consequently, there will be an advantage for the primed region when it is presented in the matching display.

In contrast, when the study display does contain a strong figure–ground cue, the sequence of events will be

different. When the primed region is consistent with the figure–ground cue in the ambiguous study display, there will be an advantage for this region when it appears in the matching display. However, when the primed region is actually the region of the ambiguous study display that is organized as ground, the cue will counteract the effect of priming, reducing or even eliminating any advantage for the primed region in the matching display.

In this way, the PSTVM procedure may provide a novel means to examine the time course of using particular cues for resolving figure–ground relations. For instance, by varying the time allowed for the study phase, we can manipulate whether there is time for any inherent cue to counteract any effect of the prime, when the two are pitted against one another. With a relatively long study phase, we can expect matching to be biased by the figure–ground organization suggested by the cue. With a short study phase, either the prime may dominate or the effects may cancel out. In the present study, we applied the PSTVM procedure to study the time course of figural reversal due to the lower region cue for figure–ground coding (Vecera et al., 2002).

In our first experiment, we replicated the result reported by Vecera et al. (2002). We considered this pru-

dent for two reasons. First, most of the evidence provided for this cue has been derived from explicit reporting methods which, as we have pointed out above, might be open to top-down influences. Second, in their final experiment, Vecera et al. used the STVM task to provide converging evidence from an implicit method. They reported a matching advantage of around 35 msec for lower regions of displays, which indicates that the lower region of an ambiguous figure-ground display is more likely to become organized as figure thus generating a matching advantage. However, some aspects of the data in Vecera et al. seem to indicate that their STVM task was quite difficult. For instance, the RTs in the original STVM task reported by Driver and Baylis (1996) were 1,100 msec or less, whereas the RTs in Vecera et al. were at least 1,300 msec. Moreover, the error rate was 27.2% in Vecera et al., rather than the 17% or lower that Driver and Baylis reported. We therefore thought that it would be useful to assess the stability of the lower region effect before we began exploring the time course of figural reversal in an ambiguous figure-ground display.

GENERAL METHOD

Apparatus

A Pentium III PC controlled the experiment and presented the stimuli on a 17-in. VGA monitor, in 640×480 graphics mode.

Stimuli

An example of the stimuli used in this experiment is shown in Figure 2. The stimuli contained 10 bars, each 0.7° wide. The first 5 bars from the left were randomly given a length between 2° and 4.5° . The remaining 5 bars were given a length of 6.5° minus the length of the corresponding bar. Bars were paired from the outside in. This resulted in a shape that, when rotated 180° , made a perfect jigsaw match with itself. Presented on its own, a jigsaw half would be used as prime. Adding the two jigsaw halves together resulted in a square of $6.5^\circ \times 6.5^\circ$. The square was used as a study in the ambiguous figure-ground displays. This way of generating stimuli ensured that there were no unintended differences between the upper and lower regions, because they both consisted of exactly the same shape. There were four versions of every ambiguous figure-ground display (see Figure 2): one with a black lower region and a white upper region, one with a reversed assignment of black-and-white, and mirror images of these two versions. The stimuli were presented on a gray background.

Procedure

Participants were tested individually in a session that lasted approximately 40 min. After receiving the instruction for the task, participants performed a practice block of 16 trials. When they felt at ease with the task, they started the experimental blocks, otherwise they got another practice block of 16 trials.

A trial consisted of a fixation dot presented in the center of the screen for 500 msec. After the fixation cross disappeared, the prime display was presented for 100 msec. Immediately afterward, the study display was presented for 200 msec in Experiment 2, 50 msec in Experiment 3, and 350 and 500 msec in Experiment 4. After a blank display that lasted 500 msec, the match display appeared and remained on the screen until the participant responded or 30,000 msec had passed. After the response, there was an intertrial interval of 1,000 msec before the start of a new trial. The participants' task was to decide which of the two shapes presented in the match display had previously appeared in the study display. In trials where participants had to match the lower region of the study display, the

Figure 2. Examples of ambiguous figure-ground stimuli used in Experiments 1–4. Upper and lower regions have exactly the same shape. All possible combinations of colors and mirror versions were used in Experiments 1–4.

two shapes in the match display were the lower region from the study display and its (left-right) mirror reversal. In trials where an upper region match was required, the two alternatives were the upper region from the study display and its (left-right) mirror reversal. If the shape on the left was the correct match, participants had to press the “Z” key on the keyboard as quickly as possible. If the shape on the right was the match, the “M” key was used.

Design

The factors region primed (upper region, lower region), region matched (upper region, lower region), and position of the correct answer (left, right) were fully crossed in every experiment. This resulted in each of the four versions of an ambiguous display being used eight times. There were 15 different ambiguous displays, so in total an experiment consisted of $15 \times 4 \times 8 = 480$ trials. These were presented in blocks of 64. Between every block, there was a self-paced break for the participant. If a participant made an error, the error trial was retaken somewhere in the sequence of trials.

EXPERIMENT 1 A Replication of Vecera et al. (2002)

Method

The method used in Experiment 1 was similar to that in the General Method section described above, with the following exceptions. We used the STVM presentation sequence (Figure 1A), because a replication of the experiment of Vecera et al. (2002) meant elimination of the prime display from the PSTVM presentation sequence. As a consequence, there were only 240 trials in this experiment. We used 200 msec as the study time, because this was the study time used by Vecera et al.

Stimuli and Procedure. These were as described in the General Method section.

Design. In this experiment, there was only a single factor: region matched.

Participants. Nineteen participants (17 female, 2 male) were recruited, either for course credit or for a small payment. All had normal or corrected-to-normal vision, and they were naive about the purpose of this experiment.

Results and Discussion

The results are shown in Figure 3. One participant was excluded from the analysis because of an excessive error rate ($>.3$). Responses greater or less than 2.5 *SDs* from the cell mean (region matched) for each participant were rejected, resulting in the loss of 2.6% of the data. A paired *t* test on the RT difference between upper region match and lower region match yielded a significant result [$t(17) = 2.173, p < .045$]. Lower region matches were 36 msec faster than upper region matches (945 msec and 981 msec, respectively). A paired *t* test on the error data did not yield a significant result [$t(17) = 0.781, p < .45$]. There were fewer errors for lower region matches (.10 and .11, respectively), so there is no sign of a speed-accuracy trade-off.

Like Vecera et al. (2002), we found an advantage for lower region matches. This is a clear replication of the results reported by Vecera et al. In our experiment, however, the reaction times were much faster, and the error rates were lower. An explanation for this improvement in performance probably lies in the properties of the ambiguous displays that we used in our experiment. The

upper and lower regions that we used were rotationally symmetric, which might have made the task easier by reducing the complexity of the displays. Furthermore, there were only upper and lower region matches in our experiment, whereas the experiment reported by Vecera et al. also contained left and right region matches. Vecera et al. have suggested that figure-ground displays that contain a figure-ground cue might take longer to process than totally ambiguous displays. Our result shows, however, that displays with a clear figure-ground cue can be processed quite quickly. The 200-msec study time seems to give enough scope to resolve any ambiguity in figure-ground assignment.

The combination of the results reported by Vecera et al. (2002) and those of our replication firmly establishes the lower region as a valid figure-ground cue. In the following experiments, we will try to look more closely at the processes involved when the figural interpretation of an ambiguous figure-ground display changes.

In order to do this, we will introduce a 100-msec prime into the presentation sequence that we used in Experiment 1. This yields the PSVTM sequence (Figure 1B).

Figure 3. Results of Experiment 1, a replication of the study of Vecera et al. (2002). The dotted lines indicate the RTs and error proportions observed in the original study by Vecera et al.

We chose 100 msec as the duration of the prime because this is the upper limit of the time when differences start to appear in the response of cells in V1 of macaques when their receptive fields contain either the figure or the ground part of a stimulus (Lamme, Zipser, & Spekreijse, 1998). When the prime does indeed influence the subsequent interpretation of the ambiguous study display, we would expect an effect of the prime.

Specifically, we would still expect a matching advantage for lower regions after a lower region prime. As we suggested in the introduction, priming the dominant region of the ambiguous figure-ground display will only result in setting participants off with a figure-ground interpretation that they would have reached anyway at the end of the study period. However, we expect a reduced matching advantage for lower region after an upper region prime. The upper region prime will confer figural status on the upper region of the study display. Experiment 1 has shown, though, that this is not the preferred interpretation of the ambiguous display. We therefore expect that there will be a reassignment of figure and ground. If 200-msec study time is not enough to complete this reassignment, this should result in a reduction of the matching advantage for the lower region. Consequently, we expect an interaction between region primed and region matched, because there will only be a lower region advantage after a lower region prime.

EXPERIMENT 2

Priming With 200-msec Study Time

Method

The details are provided in the General Method section. The study time used in this experiment was 200 msec.

Participants. Fifteen participants (11 female, 4 male) were recruited either for course credit or for a small payment. All had normal or corrected-to-normal vision, and they were naive about the purpose of this experiment. None had participated in the previous experiment.

Results

The results are shown in Figure 4. Responses greater or less than 2.5 *SDs* from the cell mean (region primed $\times$ region matched) for each participant were rejected, which resulted in the loss of 2.6% of the data. The error analysis was performed on all of the remaining trials, whereas the RT analysis only used the correct trials.

A two-way repeated measures analysis of variance (ANOVA; region primed $\times$ region matched) on the RT data revealed both a significant main effect of region matched [$F(1,14) = 18.4, p < .001$] and a significant interaction between region primed and region matched [$F(1,14) = 7.7, p < .015$]. A planned contrast showed only a lower region effect when the lower region was primed [$t(14) = 4.90, p < .001$], whereas the lower region effect did not materialize when the upper region was primed [$t(14) = 0.34, p < .74$]. There were no significant effects in a comparable ANOVA on the error rates ($F_s < 1.9$).

Discussion

After an upper region prime, there was no matching advantage for the lower region, whereas the lower region advantage stayed intact after a lower region prime. This result suggests that 200-msec study time is not enough to undo the figure-ground assignment enforced by the upper region prime. On the other hand, it also suggests that the reassignment process is underway after 200 msec and already has put the upper region and the lower region on an equal footing. Otherwise, we would expect a matching advantage for the upper region after an upper region prime.

It seems that a 100-msec exposure to a display with an unambiguous figure-ground arrangement is long enough to establish this assignment. This indicates that the results of the single cell recordings reported by Lamme et al. (1998) seem to extend to behavioral figure-ground research in humans as well. The assignment of figure and ground seems to be a very rapid process for unambiguous displays.

After 200 msec, the reassignment of figure and ground in the study displays has had sufficient time to reduce the benefit that the upper region otherwise would have enjoyed after an upper region prime, but not enough time to reestablish the advantage normally enjoyed by the lower region. This prompts two questions: How long is long enough, and when is the study time too short? In Experiment 3, we will address the latter question, and in Experiment 4 the former.

EXPERIMENT 3

Priming With 50-msec Study Time

Method

The details are provided in the General Method section. The study time in this experiment was 50 msec.

Participants. Sixteen participants (12 female, 4 male) were recruited either for course credit or for a small payment. All had normal or corrected-to-normal vision, and they were naive about the purpose of this experiment. None had participated in the previous experiments.

Results

The results are shown in Figure 5. Responses greater or less than 2.5 *SDs* from the cell mean (region primed $\times$ region matched) for each participant were rejected, which resulted in the loss of 2.7% of the data. The error analysis was performed on all of the remaining trials, whereas the RT analysis only used the correct trials.

A two-way repeated measures ANOVA (region primed $\times$ region matched) on the RT data revealed both a significant main effect of region matched [$F(1,15) = 7.48, p < .016$] and a significant interaction between region primed and region matched [$F(1,15) = 12.7, p < .003$]. As in Experiment 2, a planned contrast showed only a lower region effect when the lower region was primed [$t(15) = 3.69, p < .003$], whereas the lower region effect failed to materialize when the upper region was

Figure 4. Results of Experiment 2: study time of 200 msec.

primed [$t(15) = 1.27, p < .23$]. There were no significant effects in a comparable ANOVA on the error rates ($F_s < 3.48$).

Discussion

The pattern of results is essentially the same as in Experiment 2. Again, there is a clear advantage for a lower region match after a lower region prime. And again, there is no advantage for either the lower or upper region after an upper region match. There seems to be an almost instantaneous reset of the current figure-ground assignment when a cue becomes available that suggests that the assignment of figure and ground should be reversed. Only 50 msec of exposure to the ambiguous display is enough to abandon the result of the previous figure-ground assignment.

However, there is an alternative interpretation. It might be the case that the results that we have observed in all the previous experiments are caused by effects in the matching displays, rather than effects in the priming and study displays. If the lower regions in the match displays were more easily organized as figure than were the upper regions, we would expect similar effects. Lower region matches would always be faster because it is easier to determine figure and ground in the match display. The lack of a matching advantage after an upper region prime would result from the slower determination of fig-

ure and ground in a match display containing upper regions that cancel out the priming effect of the upper region. We will test this alternative in Experiment 5. Before that, we will investigate whether it is possible to observe a lower region advantage even after an upper region prime. A longer exposure to the ambiguous study display should give the lower region cue enough time to determine the figural interpretation and leave a memory trace that is sufficiently strong to produce faster matches for lower regions. In Experiment 4, we increased the study time to 350 and 500 msec.

EXPERIMENT 4

Priming With 350- and 500-msec Study Times

Method

The details are provided in the General Method section. The two study times used in this experiment were 350 and 500 msec.

Participants. Thirty-two participants (23 female, 9 male) were recruited either for course credit or for a small payment. All had normal or corrected-to-normal vision, and they were naive about the purpose of this experiment. None had participated in the previous experiments. The participants were randomly allocated to the two study times, 16 to each.

Results

The results are shown in Figure 6. One participant in the 350-msec condition was excluded from the analysis

Figure 5. Results of Experiment 3: study time of 50 msec.

because of an excessive error rate ($>.3$). As before, responses greater or less than 2.5 *SDs* from the cell mean (region primed $\times$ region matched) for each participant were rejected, resulting in the loss of 3.2% of the data for the 350-msec prime and 2.8% of the data for the 500-msec prime. The error analysis was performed on all of the remaining trials, whereas the RT analysis only used the correct trials.

A two-way repeated measures ANOVA (region primed $\times$ region matched) on the RT data for the 350-msec prime yielded only a significant main effect of region matched [$F(1,14) = 9.2, p < .001$]. As before, this is a reflection of the lower region effect. Neither the main effect of region primed nor the interaction between region primed and region matched reached significance [$F(1,14) = 3.18, p < .10$, and $F(1,14) = 0.424, p < .53$, respectively]. A similar ANOVA on the error rates did not show any significant effects ($F_s < 1.78$).

A two-way repeated measures ANOVA on the RT data for the 500-msec prime similarly only revealed a significant main effect of region matched [$F(1,15) = 7.91, p < .014$]. Again, neither the main effect of region primed nor the interaction between region matched and region asked were significant ($F_s < 1.38$). In the error analysis, the main effect of region matched yielded an $F(1,15) = 4.32, p < .06$, indicating a trend toward fewer errors for lower region matches. The main effect of region primed

and the interaction between region primed and region matched failed to reach significance ($F_s < 0.36$).

Discussion

Contrary to the results of Experiments 2 and 3, we now only observed a matching advantage for lower regions. Independent of whether the preceding prime was an upper region or a lower region, the lower region matches were always faster than the upper region matches. This result suggests that the reassignment of figure and ground is complete when the study display is presented for 350 msec. Adding another 150 msec does not change the outcomes.

Apparently, it takes between 200 and 350 msec to reverse a figural assignment that is incongruent with the available figure-ground cues. If we plot the results of Experiments 2–4 together (Figure 7), we see that varying the duration of the study display after a lower region prime seems to have little influence on the size of the lower region advantage. The lower region advantage is already entrenched after 50 msec, and prolonging the duration of the study display to 500 msec does not seem to alter the advantage. This suggests that the lower region prime effectively shortcuts the figure-ground assignment process and that the prime alone already gives the strongest possible advantage. The subsequent study displays are unable to boost this advantage any further,

Figure 6. Results of Experiment 4: (A) study time of 350 msec; (B) study time of 500 msec.

which suggests that the assignment of figure and ground in an unambiguous display is at ceiling after 100 msec.

The results with the upper region prime show quite rapid changes in figure–ground assignment when the study display contains a figure–ground cue that contradicts the current figure–ground assignment. After only 50 msec, the previous assignment has effectively been annulled, and after 200–350 msec, a reversal of the figure–ground assignment has been completed.

Before we are able to accept this interpretation, however, we must demonstrate that we are not simply looking at effects that are restricted to the matching display. If there were a difference in the strength of the figural interpretation of an upper region and a lower region, we would expect a difference in the speed with which participants are able to match a region with its prime. Matching a lower region to its prime should be fast. Not only would the prime leave a stronger memory trace, but the matching process itself should be faster, because it is easier to decide on figure and ground in the matching display. Matching an upper region to its prime should be slower, because the upper region prime leaves a weaker memory trace and because it is more difficult to decide on figure and ground in the matching display.

Another alternative explanation of the results obtained by the increase in study time in Experiment 4 would be

that the prime might bypass the study display and influence the match display directly. In this case, the decrease in the effect of the upper region prime might be attributable to a decay of the effect from the prime on the match display: An increase in the duration for which participants can study the ambiguous display, it also increases the time between the prime display and the match display. In this scenario, there would be no role for the study display and hence, the results we have obtained so far would not reflect any processes involved in assigning figure and ground.

So if there are differences in the figural strength of upper and lower regions per se or if the prime bypasses the study display, we would expect a lower region advantage even in the absence of a study display. That is, it should be easier to match a lower region to a lower region prime than to match an upper region to an upper region prime. In our final experiment, we will test these hypotheses by omitting the ambiguous figure–ground display from the PSTVM sequence. This yields an STVM sequence where we have an unambiguous study display followed by a matching display (Figure 1C). To emphasize the relationship with Experiments 2–4, we will call this priming with 0-msec study time, because of the total absence of the ambiguous display.

Figure 7. Results of Experiments 2–4, presented as lower region advantage as a function of region primed and study time. The lower region advantage is computed as the difference in RT between an upper region match and a lower region match.

EXPERIMENT 5 Priming With 0-msec Study Time

Method

The method used in Experiment 5 was similar to that used in the previous experiments, with the following exceptions. The 0-msec study time condition effectively means the elimination of the study display from the PSTVM sequence, making it an STVM sequence with an unambiguous study (Figure 1C). As a consequence, only the primed region can be matched, because the primed region (displayed for 100 msec) is the only region that the participants have seen previously. There were therefore only 240 trials in this experiment.

Stimuli and Procedure. These were the same as in the previous experiments.

Design. In this experiment, there is only a single factor: region matched.

Participants. Fourteen participants (10 female, 4 male) were recruited either for course credit or for a small payment. All had normal or corrected-to-normal vision, and they were naive about the purpose of this experiment. None had participated in the previous experiments.

Results and Discussion

The results are shown in Figure 8. As before, responses greater or less than 2.5 *SDs* from the cell mean (region matched) for each participant were rejected, resulting in the loss of 2.6% of the data. A paired *t* test on the RT difference between upper region matched and lower region matched did not yield a significant result [$t(13) = 0.15$, $p < .88$]. Lower region matches were 1 msec faster than upper region matches (719 msec and 720 msec, respectively). Lack of power does not seem a viable explanation for the lack of a significant result, because the means are virtually identical. A paired *t* test on the error data did not yield a significant result either [$t(13) = 0.76$, $p < .47$]. There were more errors for lower region matches than for upper region matches (.08 and .07, respectively). Together, these results seem to rule out any suggestion that properties of the match display somehow influenced the results that we observed. They also rule out an inter-

pretation that the results we saw in the previous experiments resulted from a direct influence of the prime on the match display. Instead, the results in the previous experiments seem to reflect the consequences of the reassignment of figure and ground due to the presence of the lower region cue in the ambiguous study display.

GENERAL DISCUSSION

We have presented data from an adaptation of the STVM paradigm (Driver & Baylis, 1996). The addition of a prime display enabled us to bias the assignment of figure and ground in the subsequent ambiguous study display. We term this adaptation the PSTVM task.

The first result of note is that we managed to replicate the results reported by Vecera et al. (2002), without producing high error rates and long RTs. Together with the results already reported by Vecera et al., Experiment 1 establishes that the lower region is indeed a strong figure-ground cue. We can dismiss the suggestion of a difference in the ease with which the lower and upper regions in the match displays are organized as figure. Experiment 5 showed that the upper regions are primed as strongly as the lower regions.

Second, the results of our experiments indicate that the differences in firing rate, contingent on figure or ground being in the receptive field, of macaque V1 cells after 100 msec, as reported by Lamme et al. (1998), might be reflected in the behavior of human observers. It seems that determining figure and ground in unambiguous displays is a very rapid process. Many visual tasks (e.g., visual search) take this rapid figure-ground assignment for granted. Only recently has the role of figure-ground assignment in visual search been tested explicitly (by Wolfe, Oliva, Horowitz, Butcher, & Bompas, 2002). In accord with our results reported here, Wolfe et al. concluded was that the search items were separated from the background preattentively.

Figure 8. Results of Experiment 5: study time of 0 msec.

The addition of a priming display enabled us to gauge the processes of figure-ground assignment more directly. In our experiments, we used the lower region cue, but the PSTVM method seems easily extendable. For any ambiguous figure-ground display, it should be possible to prime either the prospective figure region or the prospective ground region. This adds another avenue to test the strength of a figure-ground cue, together with reversal rates and other explicit methods. Moreover, when a figure-ground cue is unable to reverse the effect of priming, a significant effect of priming will indicate that the experiment was powerful enough, making the case for null effects much stronger.

With the strong lower region cue present in the ambiguous study display, we saw that the interaction between primed region and matched region was concentrated on the upper region prime, which normally would be organized as ground. It is here that the influence of the region prime actually has to be negated. Priming the lower region merely shortcuts the figure-ground assignment. The final figure-ground interpretation is available immediately after the presentation of the prime display and does not have to be further enhanced.

Our data indicate that it takes between 200 and 350 msec to fully migrate from the upper region as figure to the lower region as figure. It is interesting to see to what extent our results can be explained by one of the

most explicit models of figure-ground assignment, the parallel interactive model (PIM), proposed by Peterson, De Gelder, Rapcsak, Gerhardstein, and Bachoud-Levi (2000). In PIM, both sides of a contour in a region with ambiguous figure-ground assignment are held to compete with one other, and the winner of this competition receives a figural interpretation, and the losing side is actively inhibited. As a result of this inhibition, the background is rendered shapeless.

If we interpret the results of our experiments in terms of PIM, there are several interesting observations to make. First of all, our results suggest that, for unambiguous displays (i.e., the priming displays), the competition is settled quite quickly. It seems that 100–150 msec (the lower region cue reduces the ambiguity of the study displays) is enough to yield a clear winner. Also, increasing the presentation time of the study display from 50 to 500 msec does not seem to add to the strength of the figural interpretation generated from the prime, even though the lower region cue is available in the study display. On the other hand, there is no indication that the ambiguous figure-ground study display reduces the figural strength of the lower region. This suggests that competition for figure-ground assignment is not reopened, even though the study display was more ambiguous. However, our data indicate that, as soon as there is a change in the display that contradicts the figure-ground

assignment, the competition does reopen, even with a study display of only 50 msec. Here, when the ambiguous display contains cues that conflict with the initial figure ground interpretation, any inhibition of the ground region markedly decreases. The short time frame suggests, in fact, a continuous reevaluation of the result of the competition between the sides of the contour.

Our data also suggest that any inhibition resulting from competition between sides in an ambiguous display takes longer to develop. In particular, the study display needed to be presented for 200–350 msec to overrule (and presumably inhibit) the primed figural region. It seems that any inhibition takes longer to develop when the strength of the competing sides is more balanced.

There is also some indication that a figural interpretation based on an ambiguous display is weaker than that of a figural interpretation based on an unambiguous display. In particular, the lower region effect after a lower region prime appears to be larger than both the effect reported by Vecera et al. (2002) and the advantage we found in Experiment 1. This would imply a cost attached to the competition proposed in PIM when regions have some degree of ambiguity.

There also appears to be a positive correlation between the strength of the figure and any apparent inhibition of the ground. In VSTM, the strength of the memory trace is positively correlated with the strength of the figural interpretation. The stronger the memory trace, the larger the facilitation in the subsequent matching task, which is exactly what we observe in our experiments. The condition in which we would expect the strongest figural interpretation—a lower region prime followed by a lower region match—yields the fastest RTs. The same prime, followed by an upper region match consistently produces the slowest RTs. This suggests that the strongest figural impression is accompanied by the strongest inhibition of the ground.

The PSTVM method seems to be a useful addition to the armory of figure-ground studies. Because two display durations (priming time and study time) can be manipulated, questions about the stability of figural interpretations, the strength of figure-ground cues, and the time course of figure-ground assignment can be put to the test more easily.

REFERENCES

- BAYLIS, G. C., & CALE, E. M. (2001). The figure has a shape, but the ground does not: Evidence from a priming paradigm. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 633–643.
- DRIVER, J., & BAYLIS, G. C. (1996). Edge-assignment and figure-ground segmentation in short-term visual matching. *Cognitive Psychology*, **31**, 248–306.
- GIRGUS, J. J., ROCK, I., & EGATZ, R. (1977). The effect of knowledge of reversibility on the reversibility of ambiguous figures. *Perception & Psychophysics*, **22**, 550–556.
- HULLEMAN, J., & HUMPHREYS, G. W. (2004). A new cue to figure-ground coding: Top-bottom polarity. *Vision Research*, **44**, 2779–2791.
- LAMME, V. A. F., ZIPSER, K., & SPEKREIJSE, H. (1998). Figure-ground activity in primary visual cortex is suppressed by anesthesia. *Proceedings of the National Academy of Sciences*, **95**, 3263–3268.
- PALMER, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.
- PETERSON, M. A., DE GELDER, B., RAPCSAK, S. Z., GERHARDSTEIN, P. C., & BACHOUD-LEVI, A. C. (2000). Object memory effects on figure assignment: Conscious object recognition is not necessary or sufficient. *Vision Research*, **40**, 1549–1567.
- PETERSON, M. A., & GIBSON, B. S. (1994). Must figure-ground organization precede object recognition? An assumption in peril. *Psychological Science*, **5**, 253–259.
- PINNA, B., WERNER, J. S., & SPILLMANN, L. (2003). The watercolor effect: A new principle of grouping and figure-ground organization. *Vision Research*, **43**, 43–52.
- STRÜBER, D., & STADLER, M. (1999). Differences in top-down influences on the reversal rate of different categories of reversible figures. *Perception*, **28**, 1185–1196.
- VECERA, S. P., VOGEL, E. K., & WOODMAN, G. F. (2002). Lower region: A new cue for figure-ground assignment. *Journal of Experimental Psychology: General*, **131**, 194–205.
- WOLFE, J. M., OLIVA, A., HOROWITZ, T. S., BUTCHER, S. J., & BOMPAS, A. (2002). Segmentation of objects from backgrounds in visual search tasks. *Vision Research*, **42**, 2985–3004.

NOTE

1. Because there is no neutral baseline in the STVM method, there could also be a disadvantage for the region that was previously coded as ground in the study display. For the sake of consistency, we will be using the established terminology throughout this paper and will refer to the faster RTs involving regions previously perceived as figure as an *RT advantage*.

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