Comparison and Summary: Experimental Evaluation of *Data-Driven Spots*

Figures 3.74 through 3.76 compare the average performances for *C0-C7*, linear fit lines, and the average performance for the *Side-by-side*, for each *Target Display Type* group.

Color-Color

The results for the two *Color-Color* sessions are nearly identical, as the graph in Figure 3.74 shows. Error rates for *C0-C7* fall well below the *Side-by-side* for both experiments, and a comparison of *C7* with the *Side-by-side* shows the difference is significant ($p < 0.001$). The linear fit equations are given in Equations 3.16 and 3.17. Both experiments only show small decreases in performance between *C0* and *C7*, only 3% for the pilot study and 2% for the main study – neither value is of practical significance. This shows that DDS alpha-blended layers with different colors remain distinguishable in images with up to six alpha-blended layers. It would be interesting to investigate a combination of pastel colors with primary colors in a DDS layered image. It would also be interesting to evaluate experimentally how many DDS alpha-blended layers can be distinguished at once.

The linear models for the *Color-Color* sessions:

Pilot study:	0.048 + 0.004 * distractors	3.16
Main experiment:	0.060 + 0.003 * distractors	3.17

Color-Bump

The results for the *Color-Bump* sessions are also very close, with one exception: performance for the *Side-by-side-View* conditions appear to be better in the pilot study than in the main study. This could simply be due to the luck of the draw – the random assignment of participants to *Color-Bump* session in the pilot study. Because participants only completed one session in the pilot study, if the individuals assigned to the *Color-Bump* session were better at side-by-side comparisons than the participants assigned to the other sessions, a result like this would be possible. In the main study all participants completed all three sessions, so individuals who performed well at side-by-side comparisons would affect all three groups equally. A more likely explanation is that performance on the side-by-side images was influenced by the spot sizes of the alpha-blended layers. In the pilot study the target spot sizes were smaller for both layers: 0.5 for the alpha-blended layer and 0.14 for the bump-mapped layer, whereas in the main study the spot sizes were 0.83 for the alpha-blended layer and 0.4 for the bump-mapped layer.

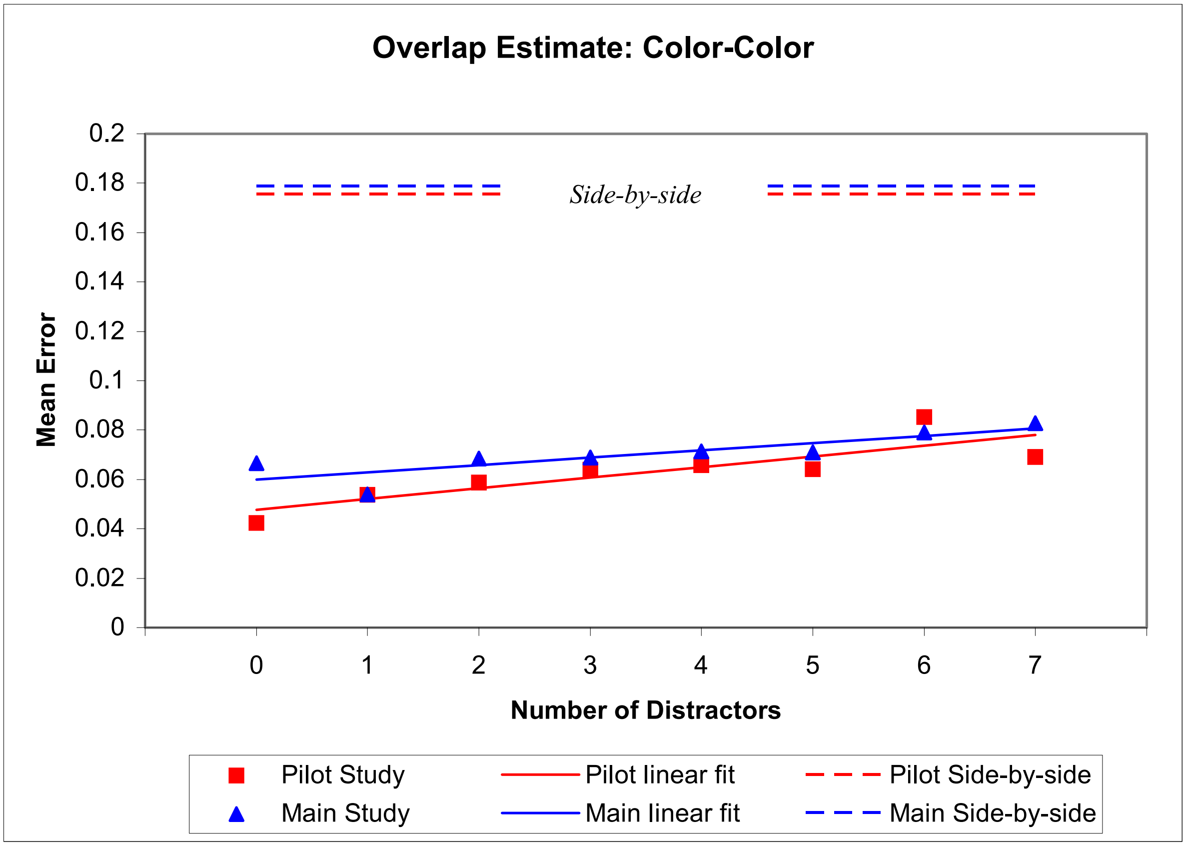

Figure 3.74: Comparison of the *Color-Color* groups between pilot and main studies. The results are identical.

The difference in performance between *C0* and *C7* is 8% and 5% for each session, an increase of 2x error for both. In both cases performance starts out like the *Color-Color* sessions for low numbers of distractors and becomes like the *Bump-Bump* sessions for larger numbers of distractors. This makes intuitive sense when all six sessions are compared, see Figure 3.77.

The linear models for the *Color-Bump* sessions:

Pilot study:	0.039 + 0.011 * distractors	3.18
Main experiment:	0.053 + 0.007 * distractors	3.19

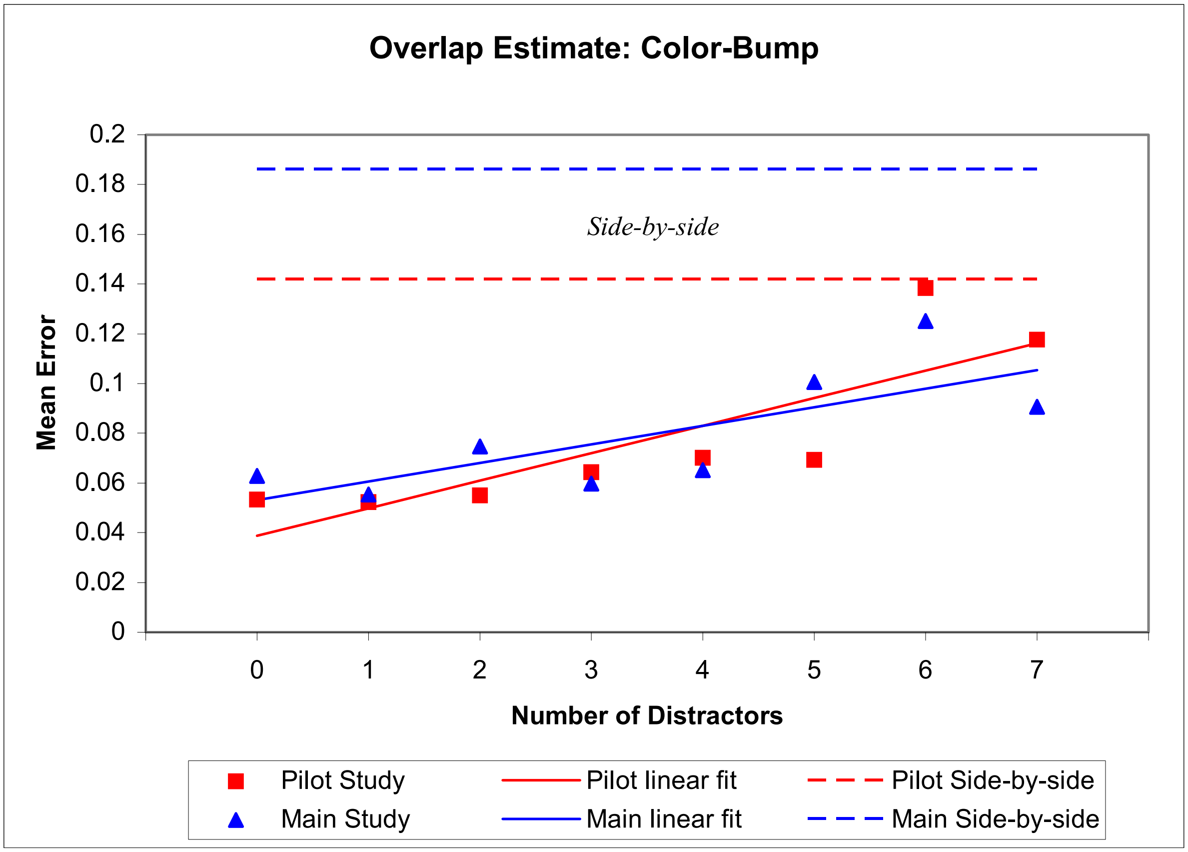

Figure 3.75: Comparison of the *Color-Bump* groups. The results are very close, with the exception that performance for the *Side-by-side-View* condition for the pilot study has much lower error on average; see the text for further discussion.

Bump-Bump

The difference between the *Bump-Bump* sessions is dramatic. There is a relative low distractor-effect for the main study, where the maximum number of DDS bump-mapped layers was three – there is only a 3% difference in performance between *C7* and *C0*. The effect of distractors is much stronger in the pilot study, where the maximum number of DDS bump-mapped layers was four. The increase in error between *C7* and *C0* is 10%, from 6.5% error at *C0* to 16.5% error (linear fit predicted values) – 2.5x increase in error.

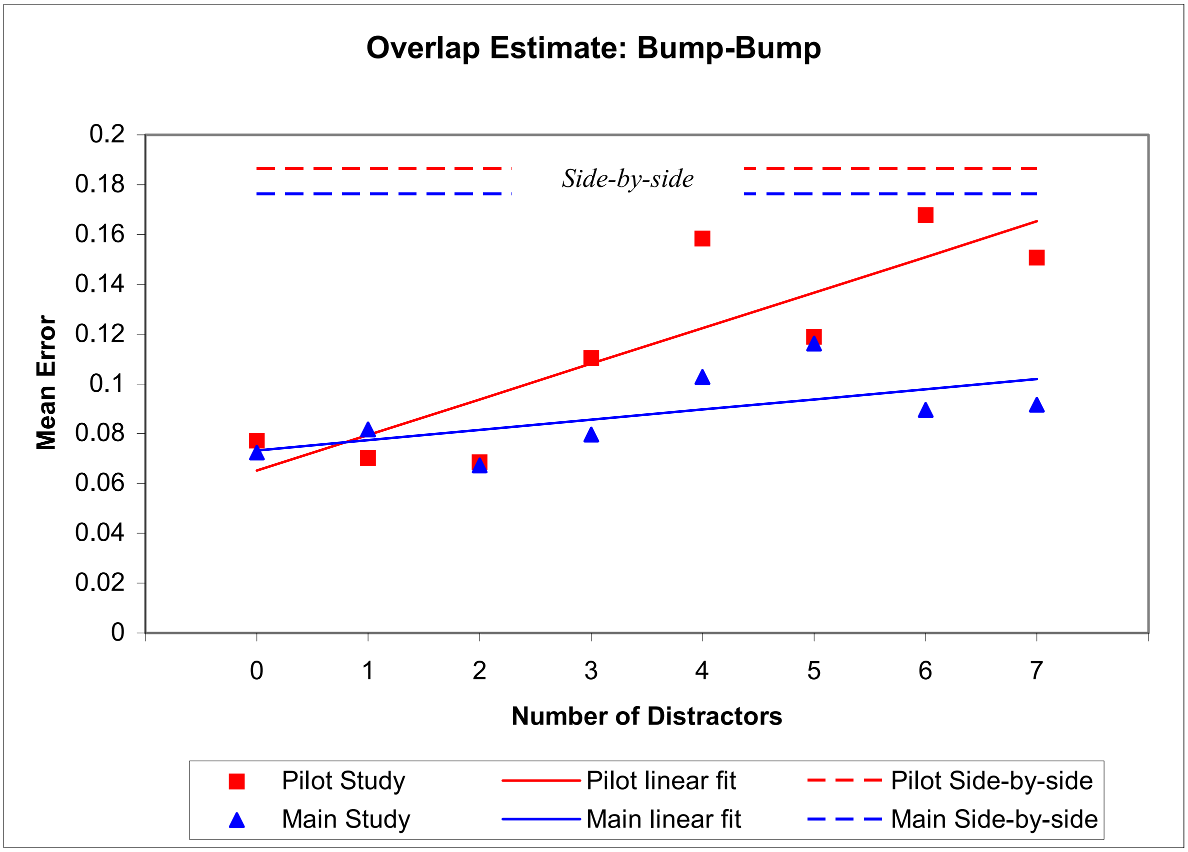

Figure 3.76: Comparison of the *Bump-Bump* groups. Here the distractor effect of bumps on top of other bumps is the most evident. For the four bump case the linear fit of performance (solid red line) approaches the performance for the *Side-by-side-View*, while the three bump case remains significantly below the *Side-by-side-View* performance.

Based on these results, it is clear that four DDS bump-mapped layers is too confusing – people do not see differences in the bump layers easily, causing them to make mistakes and have increased error. Perhaps the parameters for the four bump layers are not different enough to be easily distinguishable, or perhaps three represents a maximum number of distinguishable DDS bump-mapped layers. I believe the results indicate that bump-map layers interfere more with other bump-map layers, whereas there is little interference among alpha-blended layers.

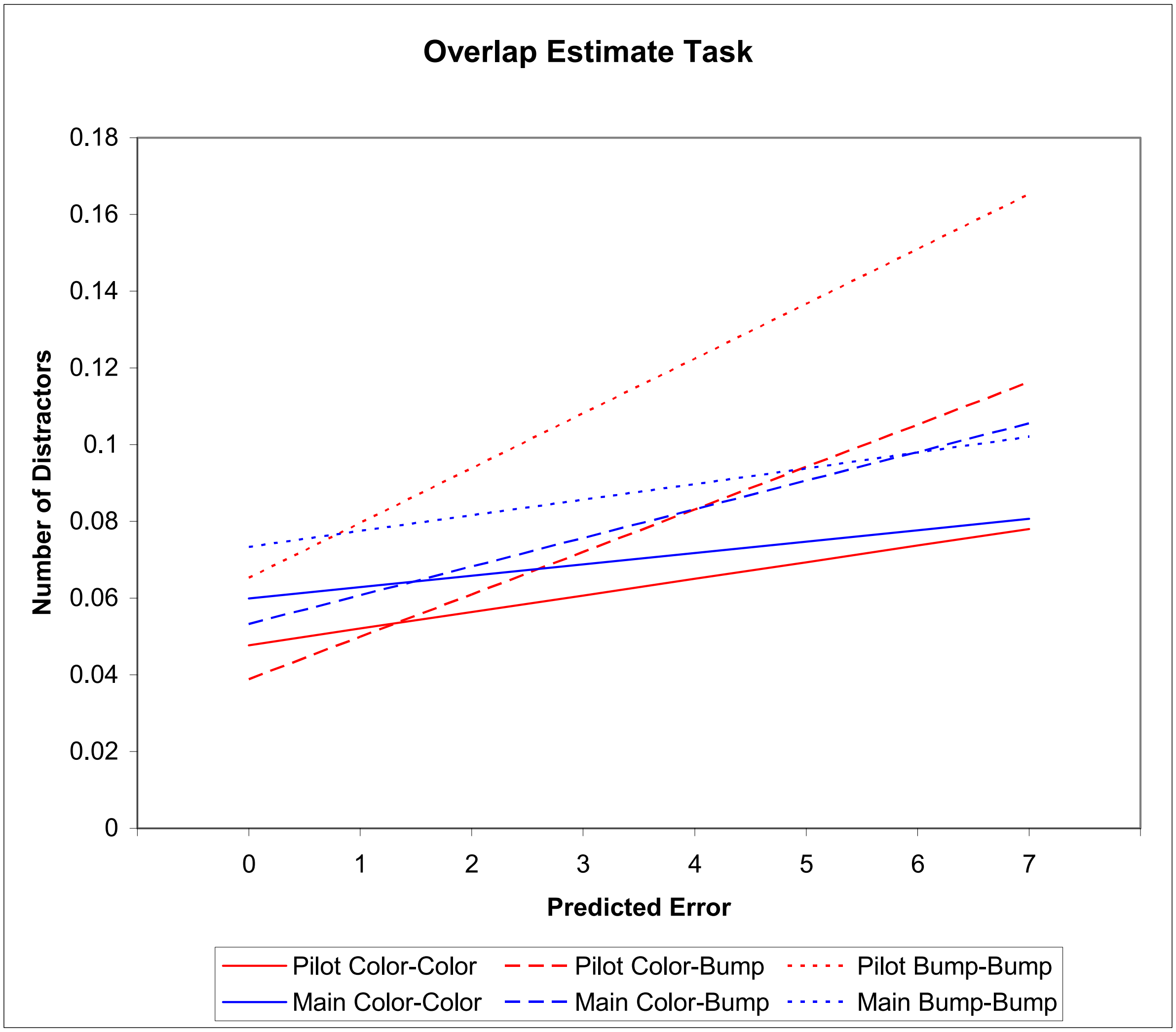

Figure 3.77: Linear fit for the two experiments, by *Target Display Type* group. The results for the *Color-Color* and *Color-Bump* groups are closely matched, while the results for the *Bump-Bump* group in the condition with up to four bump layers has a dramatic increase in error with the number of distractors.

Comparing performance between the *Bump-Bump* and *Color-Color* groups for the main study, both have small increases in error – 3 and 2%. However, performance for the *Bump-Bump* group overall is on average 2% higher than for the *Color-Color* group – comparing the linear fit lines for both groups shows the *Bump-Bump* line to be parallel but above the *Color-Color* line (see Figure 3.77). One conclusion is that the DDS bump-mapped layers were less discriminable than the DDS alpha-blended layers. It would be interesting to evaluate experimentally images with a maximum of two DDS bump-mapped layers – perhaps performance would approach that of the DDS alpha-blended layers.

The linear models for the *Bump-Bump* sessions

Pilot study:	0.065 + 0.014 * distractors	3.20
Main experiment:	0.073 + 0.004 * distractors	3.21

Summary and Discussion

Both experiments produced the same results for the *Color-Color* and *Color-Bump* sessions, despite differences in experimental design and display parameters: color is a useful factor for discriminating between multiple DDS alpha-blended layers. The replication of the results greatly increases the strength of these findings.

The difference in results for the *Bump-Bump* sessions also strengthens the conclusion that DDS bump-mapped layers are strongly affected by the number of distractors in the images, specifically by the number of other bump-mapped layer distractors (Figure 3.76).

The results of the experiment and analysis show that the DDS data visualization technique 1) is significantly better than viewing the data side-by-side and 2) can display up to nine layers of information with a combination of alpha-blending and bump-mapping, with little practical change in performance for the DDS alpha-blended layers and with only a slight decrease in performance for the DDS bump-mapped layers.

Based on the analysis of the first research question, it is clear that when two or more spatial variables exist on the same surface, overlaying the data variables in a single image is superior to looking at them in separate, side-by-side images. This is especially true if the viewer is interested in answering questions about the joint spatial distribution of the variables.

The analysis of the second research question shows that adding additional data variables to the image doesn't interfere much at all with a person's ability to evaluate the spatial correlation of two of the variables displayed. This is strong evidence that DDS layers are visually discriminable from one another, even in images with up to nine DDS layers of information.

The third question the experiment sought to answer was whether or not DDS alpha-blended layers were easier to see (i.e. were easier to visually discriminate from each other and from the DDS bump-mapped layers) than the DDS bump-mapped layers. The answer to this question is a strong yes. The results clearly show that DDS alpha-blended layers are better than the DDS bump-mapped layers for both the overlap estimation task and the intersection sketch task. Performance was best for the *Color-Color* group and worst for the *Bump-Bump* group. From this we can conclude that layer discrimination based on the size and color of the alpha-blended spots was easier than discrimination based on the size of the bumps.

The third result has clear implications for the field of data visualization. Most multivariate visualization techniques that overlay variables use shape or texture characteristics to discriminate among layers and use color to display quantitative information. What I have shown in the development of the DDS visualization technique and its experimental evaluation is that color is a much better discriminator than shape.

The DDS data visualization technique has two potential weaknesses. First, the overlapping layers might interfere with one another so that the benefit of overlaying the data for performing spatial correlation tasks would be severely reduced. The results of the experiment with DDS have clearly shown this not to be the case. The overlapping layers do not hinder task performance.

The second weakness, the key component of DDS that enables layering in the first place, is the spatial sampling of data points across the data image space. This sampling means that not all the data points for any one variable are displayed; only a sampling of the data points is shown. This tradeoff of detailed spatial information for multiple variable layers becomes a null argument once the DDS layers are animated, because animating a layer means that all the data points for that variable *are* displayed, not all at once but over time. Animation takes advantage of image and information integration our perceptual systems are so accomplished at, and the result is that animation reveals the entire data set, unraveling it before our eyes. Both possible weaknesses of DDS have been shown to not be true – multiple layers do not interfere due to the spatial sampling of the data and no data is lost by the spatial sampling when the sample points are animated.

As a last note, the experimental evaluation of DDS presented in this chapter uses reaction-diffusion spots to sample the layers displayed. Figure 3.78 shows an example from the main experiment with six alpha-blended layers and three bump-mapped layers. Figure 3.79 shows an alternative display of Figure 3.78, with the same target and distractor layers. All layers in Figure 3.79 are sampled with different Gaussian sampling arrays, instead of the reaction-diffusion textures used in the experiment, and all are displayed with DDS alpha-blending.

The Gaussian sampling arrays provide spots that are uniform in shape and intensity, whereas the reaction-diffusion textures may contain oblong spots and spots that are brighter than others. In addition, the Gaussian textures have a more random-looking spot placement than the reaction-diffusion textures, where ring-like patterns may emmerge. Finally, the density of the spots is more readily controlled by the Gaussian technique than the reaction-diffusion technique. Changing the density of the spots between layers adds an additional factor for distinguishing between layers. In Figure 3.79 lower layers are sampled more densely and upper layers are sampled less densely, which increases the visibility of lower layers. In my opinion the nine layers are more visually distinct in Figure 3.79 than in Figure 3.78, and I believe that sampling with the Gaussian spot arrays is better than sampling with the reaction-diffusion textures.

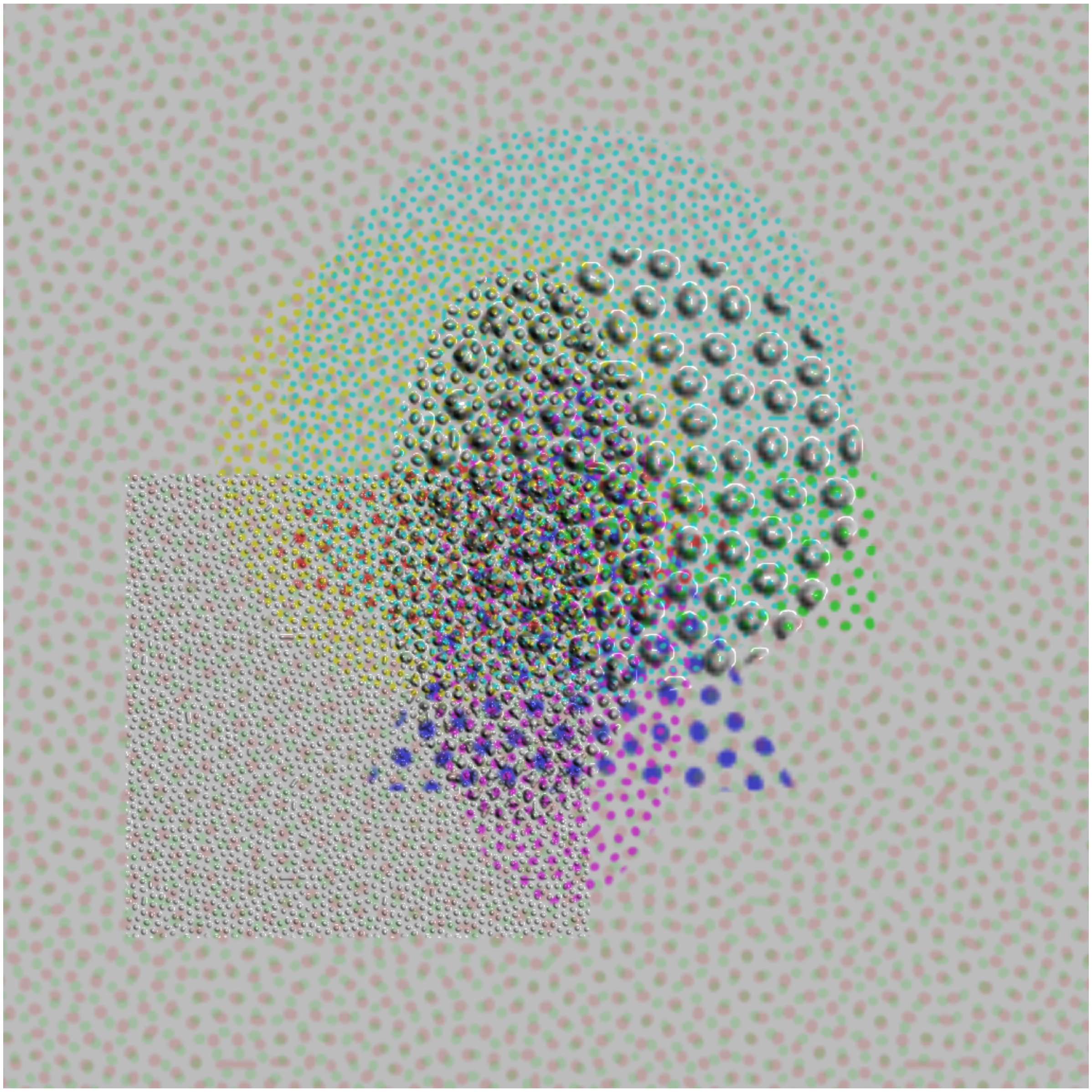

Figure 3.78: Image from *C7* for the *Color-Color* group, shown at 58% original size. Targets are the horizontal oval shown in red alpha-blended spots and horizontal rectangle shown in green alpha-blended spots. The blue triangle, large bump circle, purple oval, medium bump oval, yellow circle, small bump square and cyan circle are the distractors.

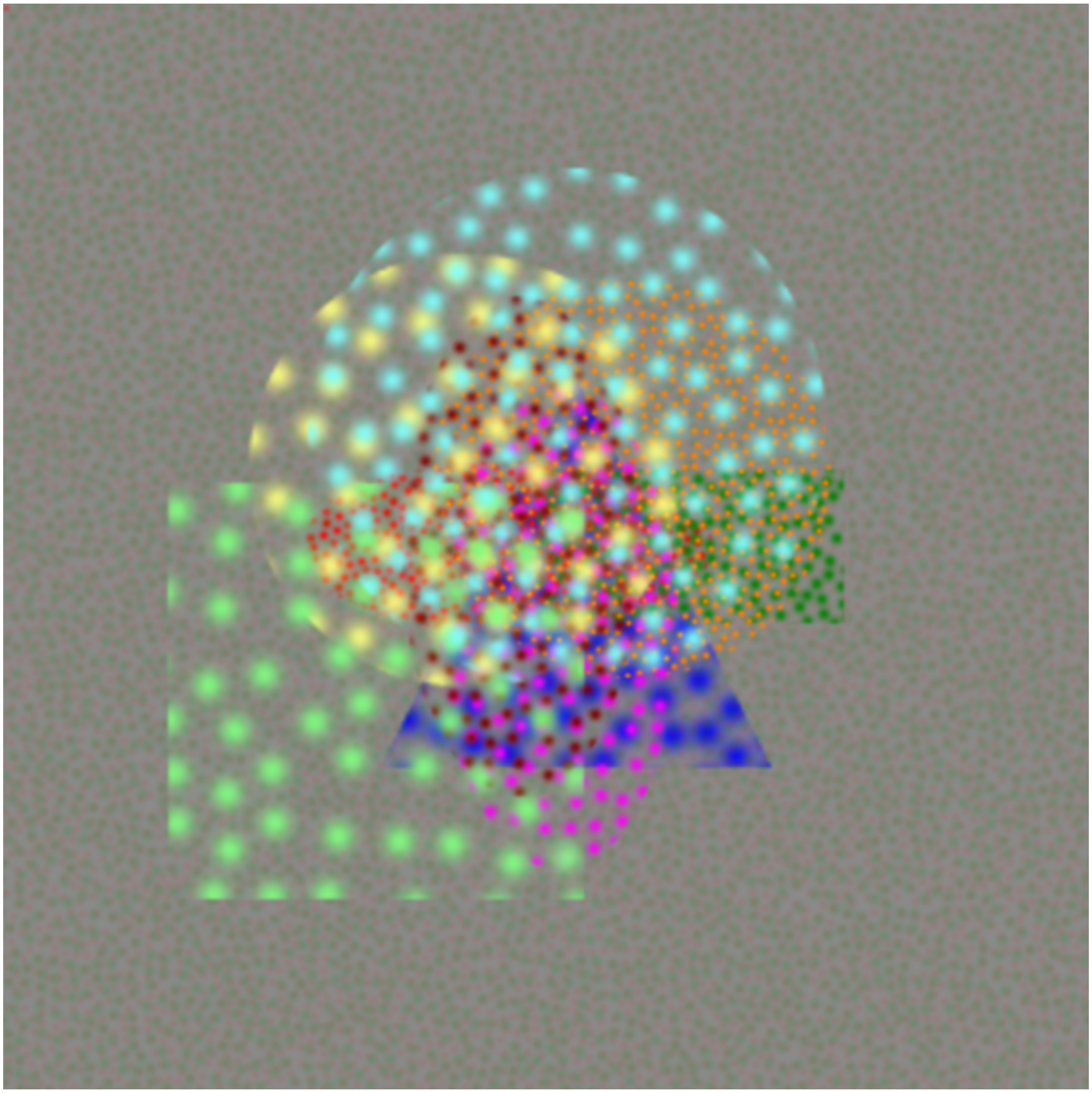

Figure 3.79: An alternative display of Figure 3.78, with the same target and distractor layer. All layers are sampled with different Gaussian sampling arrays, instead of the reaction-diffusion textures used in the experiment, and all are displayed with alpha-blending. The targets are the horizontal oval in red spots and the horizontal rectangle in green spots. Distractors are the triangle in blue spots, a purple oval, yellow circle, and cyan circle. A maroon oval replaces the medium bump oval, an orange circle replaces the large bumps, and a light-green square replaces the small bumps.