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A Structural Account of Global and Local Processing

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The order of processing, whether global forms are processed prior to local forms or vice versa, has been of considerable interest. Many current theories hold that the more perceptually conspicuous form is identified first. An alternative view is presented here in which the stuctural relations among elements are an important factor in explaining the relative speeds of global and local processing. We equated the conspicuity of the global and local forms in three experiments and still found advantages in the processing of global forms. Subjects were able to process the relations among the elements quickly, even before the elements themselves were identified. According to our alternative view, subjects created equivalence classes of similar and proximate local elements before identifying the constituent elements. The experiments required subjects to decide whether two displays were the same or different, and consequently, the results are relevant to work in higher-level cognition that stresses the importance of comparison processes (e.g., analogy and conceptual combination). We conclude by evaluating related work in higher-level cognition in light of our findings.

A central question in perception and cognition is how people process complex entities such as scenes, faces, or sentences. Processing is often characterized as either being local-to-global or global-to-local. Roughly speaking, local-to-global processing begins with local details and builds up to global configurations, whereas global-to-local operates in the reverse order, beginning with global configurations and working downward towards the details. For example, consider how people might process the profile of a face. A local-to-global algorithm would begin by recognizing an eye, a nose, and an ear, which would lead to the recognition of a face. Alternatively, a global-to-local algorithm would first recognize the outline of a face which would lead to the identification of an eye, a nose, and an ear (e.g., Palmer, 1975).

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A popular paradigm for evaluating these competing processing accounts is the nested letter identification task (Navon, 1977; Shor, 1971). Subjects observe large letters composed of several smaller letters (Fig. 1, panel a) and are instructed to identify either the larger letter (global condition) or the smaller letters (local condition). Navon showed that larger letters were identified more quickly than smaller letters. Response latencies to identify the smaller letters were affected by the larger letter (identification of the smaller letter was facilitated when the larger letter and smaller letters were the same and was inhibited when they mismatched). On the other hand, response latencies to identify the larger letter were not affected by the identity of the smaller letters. Based on these findings. Navon advanced the *global precedence hypothesis,*[1] in which the processing of the global form precedes that of the local form.

However, global advantages are not always observed (see Kimchi, 1992, for a detailed review). Varying certain qualities of the stimuli (e.g., the physical size of the letters in nested letter stimuli) can result in quicker identification of the smaller letters. Boer and Keuss (1982), Miller (1981), Grice, Canham, and Boroughs (1983), and Pomerantz (1983) advance theories in which the smaller and larger letters are processed in parallel, but the relative speeds depend, at least in part, on the conspicuity of the letters. This view accounts for a range of findings. For example, Hoffman (1980) showed that degrading information at either level can slow down processing at that level. When the larger letters are sufficiently degraded, the smaller letters will be identified first (see also Martin, 1979, for a similar effect for the density of local elements). Conspicuity can also be affected by changing the size of the nested letter stimuli. Kinchla and Wolfe (1979) show that global effects occur when the large letter of the nested letter stimuli subtends less than 7° of visual arc. However, when the size of both large and small letters is uniformly increased so that the large letter subtends more than 7°, response latencies are faster for the smaller letters. Additionally, conspicuity can be manipulated by presenting the stimuli centrally or peripherally. Lamb and Robertson (1988) have shown that peripheral presentations lead to a global advantage while central presentations do not. The upshot is that global advantage is obtained when the global letters are ‘‘easier to see’’ than the local letters and vice versa.

One determinant of conspicuity is spatial frequency. As letters become smaller, and hence have less conspicuity, they are composed of higher spatial frequencies. In nested letter stimuli, the smaller, local letters are composed of higher frequencies than the larger, global letter. A number of studies show

[1] We follow Ward (1983) and Kimchi (1992) who use the term *global advantage* to refer to the empirical phenomena of better performance on global forms in stimuli than local forms. The theoretical account that global information is utilized earlier than local information is referred to as *global precedence.*

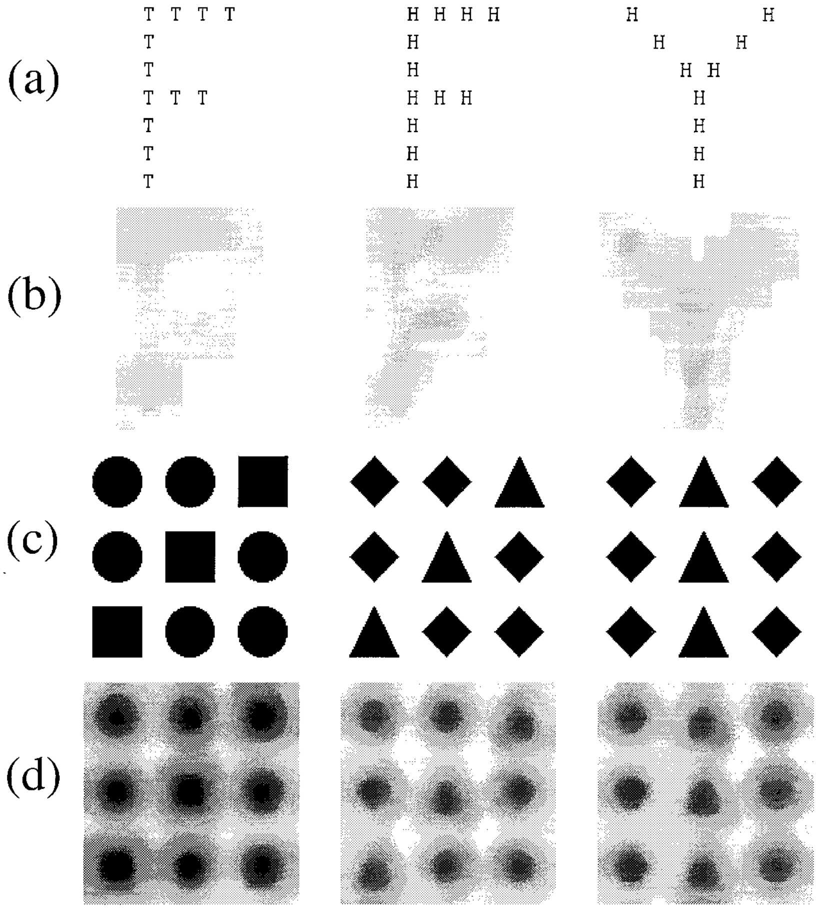

FIG. 1. Nested letter and matrix stimuli. Panel (a) shows three nested letter stimuli. The first two large ‘‘F’’s are globally similar, but they are composed of different smaller letters. The large ‘‘Y’’ is globally different from both ‘‘F’’s, but is composed of small ‘‘H’’s, and, hence, is locally similar to the large ‘‘F’’ composed of small ‘‘H’’s. Panel (b) shows the result of filtering the high spatial frequencies from the corresponding figures in panel (a), and only the large-letter form remains. Panel (c) shows three matrix stimuli. The first two matrices are globally similar (each has a diagonal pattern). The third matrix is globally dissimilar (it has a vertical bar pattern), but shares the same shape elements as the middle matrix. Panel (d) shows the results of filtering the high spatial frequencies from the corresponding figures in panel (c). Notice that filtering geometric shape matrices obscures both the local elements and the global pattern, whereas filtering nested letter stimuli differentially affects the conspicuity of local and global forms. In our matrix stimuli, the global pattern and the local elements have the same conspicuity.

that lower spatial frequency components of visual stimuli are processed more quickly than higher spatial frequencies. For example, Schyns and Oliva (1994) created pictures of scenes which were hybrids in that they combined low-frequency components of one scene with high-frequency components of another scene. Subjects were presented with these hybrid scenes for either 30 or 150 ms and asked to identify the scene. For the 30 ms presentations, subjects were more likely to identify the scene on the basis of its low-frequency components. For the 150 ms presentation, they were more likely to identify the scene on the basis of its high-frequency components. For nested letters, processing low spatial frequencies earlier than high spatial frequencies implies processing the global form before the local forms (see also Sanocki, 1993, for a spatial theory of global-to-local processing). Lamb and Yund (1993, 1996) performed a set of experiments with ‘‘contrast balanced’’ stimuli. Like Navon, they obtained a global advantage when the nested letters were drawn in white and presented on a grey background. However, this advantage disappeared when the white letters were outlined in black and presented on a grey background. The outlining procedure is called contrast balancing and has the effect of removing lower spatial frequencies. Hence, they concluded that the global advantage in the original contrast unbalanced stimuli is related to the lower spatial frequencies.

Further support for spatial frequency based accounts of global and local processing comes from work exploring the role of context in processing. For example, Lamb and Robertson (1990) have shown that the same nested letter stimuli can display either a global or local advantage, depending on context. Lamb and Robertson asked subjects to identify the global or local forms of small-, medium-, and large-sized nested letter stimuli. In one condition, only small- and medium-sized nested letters were displayed. Subjects showed global advantages with the small stimuli and local advantages with the medium-sized stimuli. In the other condition, only medium- and large-sized stimuli were displayed. Subjects showed global advantages with the medium-sized stimuli and local advantages with the large-sized stimuli. The performance on the medium-sized stimuli was dependent on the context, with local advantages in one context and global advantages in the other. When the context stressed low spatial frequencies (medium- and large-sized stimuli shown), the high spatial frequencies composing the local letters in the medium-sized stimuli were less conspicuous. When the context stressed high spatial frequencies (small- and medium-sized stimuli shown), the low spatial frequencies composing the global letters of the medium-sized stimulus were less conspicuous. A number of other researchers have shown similar context effects. In general, when manipulations stress the processing of lower spatial frequencies, a global advantage results; when manipulations stress the processing of higher spatial frequencies, the global advantage disappears and sometimes a local advantage occurs (Kinchla, Solis-Macias, & Hoffman, 1983; LaGasse, 1993; Shulman, Sullivan, Gish, & Sakoda, 1986). These results indicate that there may be a bottleneck (e.g., Pashler 1994) or limited resources (Sperling & Melchner, 1978) for processing different spatial bandwidths simultaneously and that subjects weight bandwidths differently, depending on context.

To date, explanations based on conspicuity (such as spatial frequency) are simple, elegant, and flexible enough to account for a number of conditions under which one type of processing shows advantages over the other. However, these explanations do not capture the insight that *structural* or relational properties may also be important in global processing. For example, a mechanism that grouped stimulus elements based on the Gestalt principles of similarity and proximity offers an alternative account of processing. Later, we outline how such a mechanism can predict that global pattern identification precedes local element identification. To evaluate the effect of structural properties on local and global processing, we conducted three experiments in which the conspicuity of local and global forms were equated. Thus, advantages at one level cannot be explained by differences in conspicuity. Figure 1, panel (c), shows an example of the stimuli we used in our experiments. The local elements are the simple geometric shapes (e.g., circles, squares, triangles, and diamonds). The global patterns consist of configurations of the shapes. In the first two columns of panel (c), the global pattern is a diagonal (or its figure–ground inverse). In the last stimulus of panel (c), the global pattern is a sequence of vertical bars.

To show how any advantages in identifying either global or local forms are not due to differences in conspicuity between these forms, we start by noting a distinction made by Pomerantz (1983). He uses the term *place relationships* to describe configurations in which the global form can be identified by the placement of the local elements (without regard to the identity of local elements). Nested letters are an example of place relationship configurations. In identifying the global letter ‘‘F’’ in Fig. 1, subjects do not need to identify the constituent letters as ‘‘T’’s or ‘‘H’’s. The form of the large F made of small T’s would not change if some of the T’s were replaced with H’s. The spatial frequencies conveying information about the global letter identity are not highly dependent on the characteristics of the local letters. In summary, for nested letters, it is logically possible that global identification can occur without any knowledge about the nature of the local letters.

This statement does not hold for our shape matrices. The global pattern is defined by the nature of local elements, and Pomerantz used the term *nature relationships* to describe configurations with this property. For instance, if a circle and a square in the first matrix of row (c) in Fig. 1 are interchanged, the global pattern is also changed. Therefore, to obtain the global form, the subject must determine which elements are the same and which are different. More precisely, to identify the global patterns in our stimuli, it is logically necessary to obtain the task-relevant equivalence

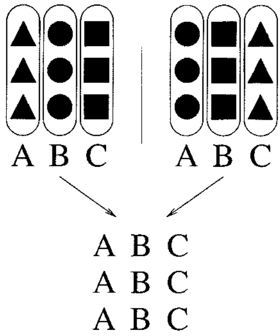

FIG. 2. The two stimuli differ locally but are different instances of the same global pattern—a sequence of vertical bars (each bar is composed of the same elements). The equivalence classes are circled and labeled ''A,'' ''B,'' and ''C.'' The stimuli have the same global pattern because they have the same spatial relationship of equivalence classes.

classes of local elements.[2] This claim is demonstrated in Fig. 2. The two stimuli are different instances of the same global pattern—a sequence of vertical bars (each bar is composed of the same elements). The equivalence classes are circled and labeled A, B, and C. The stimuli have the same global pattern because they have the same spatial relationship of equivalence classes.

For the geometric shape matrix stimuli, the conspicuity of the global pattern is the same as that of the local elements. To identify the global pattern, the observer must form equivalence classes. The conspicuity of the local elements determines the conspicuity of the equivalence classes. For example, in forming the equivalence class A in Fig. 2, it is necessary to place all the circles together in one class and exclude all the triangles from that class. Therefore, it is necessary to monitor the spatial frequencies which differentiate circles from triangles, and these spatial frequencies correspond to the scale of the local shape elements and not to the scale of the global pattern.

To further illustrate how our stimuli provide a control for conspicuity, we analyzed the spatial frequency composition of both nested letter and geometric shape matrix stimuli. Panels (b) and (d) of Fig. 1 show low pass filtered versions of nested letter and shape matrix stimuli, respectively. For nested letter stimuli, filtering out high spatial frequencies hardly affects the legibility of the larger letter while dramatically attenuates the legibility of the smaller letters. The same filtering process also makes the local elements of the shape matrices more difficult to identify. However, unlike nested letter stimuli, the

[2] The concept of equivalence class can be defined formally as a relation which is reflexive, symmetric, and transitive. It is convenient to define the relation underlying the equivalence class in terms of a metric. For example, in the shape stimuli, circles are more similar to each other than to squares, and hence the circles form one equivalence class and the squares another.

global pattern (e.g., diagonal or vertical bar pattern) is also more difficult to identify. As identification of both global patterns and local shapes depends on processing information of the same conspicuity, differences in processing speeds in our stimuli cannot be attributed to conspicuity considerations. Other studies have also used shape elements in local/global tasks (e.g., Martin, 1979, LaGasse, 1993). However, these shape element stimuli, which nest smaller shapes within larger ones, are like nested letter stimuli in that structural and conspicuity considerations covary.

There are two contrasting hypotheses to be explored with our shape matrix stimuli. The first is that local elements must be identified before equivalence classes can be formed (i.e., local-to-global processing). This hypothesis can be implemented as serial processing: first local identification occurs and then equivalence classes formation occurs by grouping identified elements. The second hypothesis is that the identity of the local elements is not necessary for equivalence class formation. There can be several processing implementations of this hypothesis. For example, equivalence class formation may strictly precede local identification in a serial fashion (i.e., global-to-local processing). Alternatively, equivalence class formation and local identification may occur in parallel. Because the conspicuity of the global form is controlled in our stimuli (panel c of Fig. 1), any observed performance advantage to the global form indicates that equivalence classes are forming prior to local identification (i.e., local identification is not determining global identification). In three experiments, we demonstrate such global advantages. Our findings indicate that subjects can process the relational aspects of the stimuli, such as the equivalence class structure, before they identify the constituent elements. This result is inconsistent with a local-to-global processing model. For more subtle reasons (which will be enumerated later), our findings are also inconsistent with a global-to-local processing model. Instead, an account that allows for some degree of parallelism is favored.

We propose the following structural mechanism which may account for how global configurations are constructed during processing prior to the identification of local shape elements. People cluster local elements according to Gestalt grouping principles such as similarity and proximity (Koffka, 1935; Kohler, 1929). For instance, local shape elements that are identical (or highly similar to each other) and proximal are very likely to be clustered. In Fig. 2, shape elements can be grouped into columns on the basis of similarity. The spatial relationship between these two groups defines the global pattern. Importantly, this grouping (which leads to the discovery of the global structure) may precede identification of the constituent elements. For instance, squares are differentiated from circles by having straight edges. Having straight edges allows for squares and circles to be segregated before one ‘‘knows’’ that one is looking at squares and circles. Analogously, two textures easily segregate when simple feature activations differentiate the two textures (Beck, 1967; Treisman & Gelade, 1980). For instance, the boundary between a texture consisting of circles and a texture consisting of squares is very discriminable because elements composing the two textures are segregated (i.e., grouped) by simple feature activations (e.g., having straight or curved edges), thus revealing the texture boundary. In this case, grouping allows for relational information (e.g., the identification of the two groups and their boundary) to become available prior to the identification of the shape elements that constitute the groups. In other words, grouping processes can enable a texture to be partitioned into broad (i.e., global) equivalence classes prior to the identification of the local shape elements.

One goal of this paper is to show that equivalence class formation can precede local identification, and hence provides an alternative mechanism for explaining global advantages. Although our grouping mechanism allows for equivalence class relations to become available prior to local element identification, it need not be the case that grouping always precedes local identification. We advocate a view in which both local identification and equivalence class formation occur in parallel. Some stimulus conditions may favor quick equivalence class formation (if the elements within the class are quite dissimilar from elements outside the class, equivalence class formation may be easier and hence be quicker). Other conditions may favor a quick local identification. For example, overlearned local elements, such as digits and letters, may be easier to identify than to group (particularly if like elements are not adjacent). We advocate an ‘‘opportunistic processing account’’ in which the system can group and then identify local elements or the reverse. The order depends on the *salience* of information pertinent to each mechanism. In the General Discussion, we elaborate on this view in light of our results.

As our explanation is based on structural rather than spatial properties, it may applicable to processing in domains other than visual perception. For example, a number of models of metaphor, analogy, and similarity use a comparison process which puts into correspondence or aligns pairs of mental representations (Falkenhainer, Forbus, & Gentner, 1989; Gentner, 1983; Goldstone, 1994; Goldstone & Medin, 1994; Holyoak & Thagard, 1989). In these models, the comparison process proceeds in a strict local-to-global fashion. In the General Discussion, we suggest that our findings provide an alternative way of viewing how comparison processes are carried out. Below, we discuss the matching paradigm that is used in the experiments and offer a processing account of the matching task.

MATCHING PARADIGMS

Subjects performed a discrimination task in which they indicated whether a standard matrix and a comparison matrix of geometric stimuli were the same or different.[3] The two matrices were considered different if any shape element in the standard matrix differed from the shape element at the corresponding location in the comparison matrix (e.g., a triangle in the upper left corner of one matrix and a square in the upper left corner of the other matrix). When the matrices were different, we varied how they were different (see Fig. 2). Sometimes the matrices had the same overall global pattern, and sometimes they had different global patterns. We also varied the number of local elements that matched.

This task is well suited for assessing whether local identification must precede equivalence class formation. To perform the task, it is sufficient to identify the local elements and compare them. In fact, comparing the equivalence classes alone is not sufficient for correct performance. The two matrices can have the same global pattern, but can still be different. If the identification of shape elements is necessary for and precedes the identification of the global pattern (i.e., local processing occurs before global processing), then information at the global level should not affect performance.

In our proposal, the global structure may be recovered prior to shape element identification through grouping. Although identifying the global pattern is not sufficient to perform the task, the global pattern does provide useful information. For instance, mismatching information at the global level is sufficient for a correct ''different'' response. In such cases, identifying the local elements would not be necessary (the number of local matches should not strongly affect performance). On the other hand, when the global structures match, a response is not possible until local elements are identified (and thus the number of local matches should strongly affect performance). Our view yields the following predictions for different trials: (1) If the global patterns are the same, performance will suffer relative to cases in which the global patterns are different. (2) As the number of local matches increases, performance will suffer. (3) There should be an interaction, with the effect of local matches becoming more prominent when the global patterns are the same compared to when they are different.

As discussed in the introduction, our opportunistic account predicts that more salient global patterns should yield larger global effects. This prediction is tested by manipulating the salience of the global patterns used in Experiment 1 (the two patterns are shown in Fig. 3). A number of factors converge to make the vertical bar pattern more salient than the other (more irregular) pattern. A nonexhaustive list of possible factors includes the proximity of identical shape elements, a shorter description length (in terms of the number of symbols required to represent a stimulus), the existence of low level visual areas that are tuned for vertically oriented stimuli, greater familiarity with

[3] In Experiment 1 and 2, the stimuli were 3×3 matrices of shape elements. In Experiment 3, the stimuli were vertical columns (i.e., 3×1 matrices) of shape elements.

the pattern, and the Gestalt principle of good form. It is beyond the scope of this paper to specify all the factors which lead to the differences in saliency between the two global patterns—the crucial point is that there are a number of factors that make the vertical bar pattern more salient than the other pattern. Although we cannot be certain which factors make one global pattern more salient than another, we can still make predictions based on pattern salience: (1) It should be harder to judge that two matrices are different when they share a salient global structure than when they share a less salient structure. (2) On the other hand, when two matrices are identical, a salient global structure should facilitate processing, allowing subjects to quickly detect that the two matrices are identical.

EXPERIMENT 1

Methods

Subjects. Twenty-seven Northwestern University undergraduate students participated for course credit.

Apparatus. The experiment was run on Macintosh LCIIIs with 12 inch Apple color monitors. The refresh rate of the monitors was 15 ms.

Stimuli. Stimuli were 3×3 matrices, each consisting of three triangles, three circles, and three squares, arranged in one of two basic global patterns (one being more salient than the other). Matrices (a) and (b) of Fig. 3 are examples of the salient global pattern, and matrices (c) and (d) are examples of the less salient global pattern. Six different versions of each pattern were constructed by rearranging the shape elements while preserving the global pattern. Each matrix was 5.5 by 5.5 cms on the screen (which subtended 7.8° of visual arc). Each shape element was 1.5 by 1.5 cms (which subtended 2.1° of visual arc).

Design. The degree of mismatch on ‘‘different’’ trials (where the correct response is ‘‘DIFFERENT’’) was manipulated at either the global level or the local level (see the previous section). These two factors were manipulated orthogonally. Examples of the four ‘‘different’’ conditions are illustrated in the bottom panel of Fig. 3. Both global patterns were used for the standard matrix on ‘‘same’’ and ‘‘different’’ trials.

Each subject participated in 288 trials, of which one third (96) were ‘‘same’’ trials. On half of these ‘‘same’’ trials, both matrices had the salient global pattern, and on the other half, both matrices had the less salient global pattern. The remaining 192 trials were ‘‘different’’ trials, with 48 trials for each of the four mismatch conditions. Again, the standard matrix in half of the trials in each mismatch condition had the salient global pattern, and half had the global less salient pattern. The order of trials was randomized for each subject.

Procedure. Subjects were seated 40 cms from the computer monitor. Each trial began with a blank white screen. The standard matrix was displayed in black for 1000 ms on the left half of the screen. 1000 ms after the onset of the standard, a fixation cross was displayed on the right half of the screen for 500 ms. After 500 ms, both the standard matrix and the fixation cross disappeared and the comparison matrix was displayed, centered where the fixation cross was centered.

The comparison matrix remained until the subjects responded. Subjects pressed the ‘‘/’’ key to indicate that the two matrices were the ‘‘same’’ and the ‘‘Z’’ key to indicate that they were different. They rested their right index finger on the / key and their left index finger on the Z key at all times. Upon response, the screen was blanked white. For correct responses, no feedback was given and the next trial began after a 1000 ms interval. For incorrect responses, the word ‘‘INCORRECT’’ was displayed in large letters in the middle of the screen

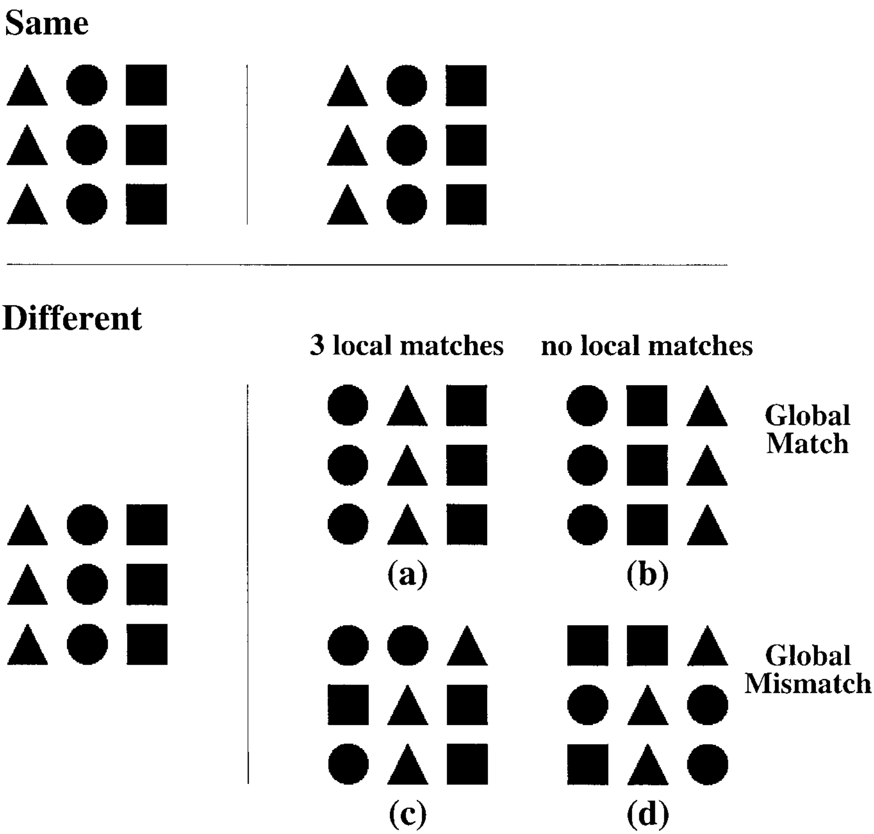

FIG. 3. The stimuli for Experiment 1. In the top panel, two identical matrixes are displayed, and the correct response is ''SAME.'' In the bottom panel, one standard and four comparison matrices are displayed. On any trial, only one comparison was displayed. The correct answer in all cases is ''DIFFERENT.''

during the intertrial interval. If the subject pressed an inappropriate key, a warning message was displayed.

A short practice session preceded the experiment. Practice trials were identical to experiment trials except that different patterns and shapes were used and feedback was given for both correct and incorrect responses. Subjects received at least four practice trials. If a subject made a mistake on a practice trial, the four practice trials were repeated until the subject responded correctly to four consecutive practice trials (this criterion was easily met by all subjects).

Results

Trials were discarded if response times were less than 200 or greater than 5000 ms (these discarded trials comprised less than one percent of the total).[4]

[4] A response latency below 200 ms was considered anticipatory. Response latencies greater than 5000 ms suggest the subject lost concentration. The specific cutoff values used to remove outliers have only small effects on medians (Ulrich & Miller, 1994).

TABLE 1
Averaged Median Correct Response Latencies and Proportion Correct for the ''Different'' Trials in Experiment 1

	Global match	Global mismatch
Standard: Salient pattern		
No local matches	842 (.97)	718 (.99)
Three local matches	967 (.87)	735 (.99)
Standard: Less salient pattern		
No local matches	800 (.97)	683 (.99)
Three local matches	883 (.88)	708 (1.00)

Subjects responded correctly on 94% of the ''same'' trials and on 96% of the ''different'' trials. Correct response latencies were 938 and 792 ms for the ''same'' and ''different'' trials, respectively. The response time and error rate advantage for ''different'' trials can be attributed to the fact that two-thirds of trials were ''different'' trials.

Different trials. Table 1 shows the averaged median correct response times for the ''different'' trials. A median correct response latency was tabulated for each subject in each condition. The entries in the table are the mean of these medians for each condition (see Ratcliff, 1993). These medians served as the dependent latency measure for subsequent ANOVA's.[5]

All three main effects were statistically significant. As predicted, subjects were slower (873 vs 711 ms) to respond ''DIFFERENT'' for trials in which the standard and comparison had the identical global pattern than for trials in which the standard and comparison had different global patterns ($F(1, 26) = 163.73$, MSe = 1413533, $p < .01$). As predicted, subjects were slower (823 vs 760 ms) to respond when there were three local matches than when there were no local matches ($F(1, 26) = 24.83$, MSe = 214358, $p < .01$). As predicted, subjects were slower (815 vs 768 ms) to respond when the standard was the salient global pattern than when it was the less salient global pattern ($F(1, 26) = 13.92$, MSe = 120204, $p < .01$). Interestingly, the degree of global match and local match interacted—when the two matrices matched globally, the effect of local match was enhanced ($F(1, 26) = 10.67$, MSe = 92153, $p < .01$). In particular, local matches slowed subjects by only 21 ms when the two matrices globally mismatched, compared to 104 ms when the matrices globally matched. No other interactions approached significance.

[5] Medians are used in all response time analyses in this paper. When analyses are performed using means, the same pattern of results emerges. We chose medians over means because medians tend to be less sensitive to outliers.

The proportion correct for each ‘‘different’’ condition is also shown in Table 1. Due to the small number of errors, these data were not analyzed. However, there was no indication of a speed–accuracy trade-off. In fact, error rates for the slower conditions tended to be higher.

Same trials. On the ‘‘different’’ trials, subjects were slower to respond when the two matrices shared the salient global pattern than when they shared the less salient global pattern. As predicted, the opposite pattern was observed for the ‘‘same’’ trials. On the ‘‘same’’ trials, subjects were slower to respond correctly when the matrices had the less salient pattern than when the matrices had the salient pattern (972 vs 905 ms, $t(22) = 2.81$, $p < .01$). Again, there was no indication of a speed–accuracy trade-off. The less salient pattern condition had a higher error rate (5% for the salient pattern and 7% for the less salient pattern). The mean response time to the ‘‘same’’ trials was slower than that to ‘‘different’’ trials. This is the reverse of what is typically observed in the literature (Luce, 1986, Ch. 10). However, in our experiment, two-thirds of all trials were ‘‘different,’’ and subjects were producing the ‘‘different’’ response about twice as often as the ‘‘same’’ response. Most likely, this factor is the cause of the quick ‘‘same’’ result.

Discussion

Our results suggest that the global pattern can be recovered prior to local element identification. As noted in the introduction, our stimuli provide a control for conspicuity (e.g., global patterns are defined by the nature of the local elements). While conspicuity explanations may hold for other data, they are not relevant in this study. We favor a processing account which involves stimulus elements being grouped into equivalence classes. Within a stimulus, identical elements are grouped together (prior to identifying or labeling the elements as circles, triangles, or squares), making it possible to identify the pattern or global structure before identifying the elements that form the structure. Thus, early in processing, two different shape matrices sharing the same global pattern will appear to match, even though the local elements mismatch. When matching global patterns are more salient, global effects are further enhanced.

In our opportunistic account, local element matches are hypothesized to affect the same–different comparison. At a local level, an element in one location of a stimulus may be recognized as identical to an element in the corresponding location of the other stimulus. When two stimuli are not the same, these kinds of matching information slow down difference judgments in predictable ways. When more local elements of a stimulus match corresponding local elements of another stimulus, subjects are slower to judge the stimuli as different than when there are no correspondences. In cases where the global structures mismatch, this effect of local matches is inconsistent with a strict global-to-local model of processing.

We also found that the processing of local and global matches interacted.

When global information matched, local matches had a greater effect in slowing down difference judgments, consistent with a global advantage. This effect is in accord with our view of processing in this task—global mismatches are sufficient for a ‘‘different’’ response, while local element identity comparisons must be performed when the global patterns match. Taken as a whole, our results are problematic for both strict local-to-global and global-to-local processing models. The results are consistent with a model that allows for some degree of parallelism.

Stroop interference is a convenient interpretation of the result that a global match slows responses on ‘‘different’’ trials. On trials where the two matrices mismatch, but globally match, the response produced by a comparison of equivalence classes is opposite that produced by comparing the identities of local elements. If comparison of local shape elements preceded equivalence class comparison, one would not expect to see Stroop interference. Our fast grouping view is consonant with a Stroop interference interpretation of the results. It provides a mechanistic account of how Stroop interference comes about in this context.

EXPERIMENT 2

Experiment 2 was identical to Experiment 1, except the presentation method was altered to test the robustness of the findings. Instead of using a delayed presentation (standard matrix shown first, followed by the comparison matrix), both matrices were shown simultaneously.

These two modes of presentation stress different aspects of processing. Experiment 1 emphasizes the memory component of processing (subjects have to retain the comparison matrix in memory). In Experiment 2, subjects are less constrained in how they can approach the task. For instance, subjects could fully encode the comparison matrix, hold it in memory, and then look at the comparison (as they must in Experiment 1). Alternatively, subjects could simply scan back and forth comparing each of the nine corresponding elements sequentially.

Methods

Subjects. Twenty-three Northwestern University undergraduate students participated for course credit.

Procedure. The procedure was similar to the procedure used in Experiment 1. Subjects were seated 40 cms from the monitor. Each trial began with the screen blank (completely white). A warning signal (which was ‘‘READY!’’) appeared in the center of the screen for 500 ms. After 500 ms, the screen went blank and both matrices were displayed simultaneously. As in Experiment 1, the standard matrix was displayed on the left side of the screen and the comparison matrix was displayed on the right side of the screen. The procedure for feedback and practice were the same as in Experiment 1 as was the response key mapping.

TABLE 2
Averaged Median Correct Response Latencies and Proportion Correct for the ‘‘Different’’ Trials in Experiment 2

	Global match	Global mismatch
Standard: Salient pattern		
No local matches	878 (.95)	847 (.98)
Three local matches	1027 (.88)	864 (.99)
Standard: Less salient pattern		
No local matches	845 (.98)	822 (.99)
Three local matches	942 (.98)	864 (.99)

Results

The pattern of results replicated that of Experiment 1. Outliers were removed, using the same criteria employed in Experiment 1. Subjects responded correctly on 93% of the ‘‘same’’ trials and on 97% of the ‘‘different’’ trials. Correct response latencies were 1447 and 886 ms for the ‘‘same’’ and ‘‘different’’ trials, respectively. The response time and error rate advantage for ‘‘different’’ trials can be attributed to the fact that two-thirds of trials were ‘‘different’’ trials.

Different trials. Table 2 shows the averaged median correct response times for the ‘‘different’’ trials. A median correct response latency was tabulated for each subject in each condition. The entries in the table are the mean of these medians for each condition. These medians served as the dependent latency measure for subsequent ANOVA’s. As in Experiment 1, all three main effects were reliable. As predicted, subjects were slower (923 vs 849 ms) to respond ‘‘DIFFERENT’’ if both the standard and comparison had the identical global pattern ($F(1, 22) = 22.32$, MSe = 250418, $p < .01$). As predicted, subjects were slower (924 vs 848 ms) to respond when there were three local matches than when there were no local matches ($F(1, 22) = 23.64$, MSe = 265240, $p < .01$). Also as predicted, subjects were slower (904 vs 868 ms) to respond when the standard was the salient global pattern than when it was the less salient global pattern ($F(1, 22) = 5.25$, MSe = 58862, $p < .05$). The degree of global match and local match interacted in the same way as in Experiment 1—when the two matrices matched globally, the effect of local match was enhanced ($F(1, 22) = 9.07$, MSe = 101708, $p < .01$). Local matches slowed subjects by only 30 ms when the two matrices globally mismatched, compared to 123 ms when the matrices matched at the global level. No other interactions approached significance.

The proportion correct for each ‘‘different’’ condition is also shown in Table 2. Due to the small number of errors, these data were not analyzed.

However, ther was no indication of a speed–accuracy trade-off. In fact, error rates for the slower conditions tended to be higher (with the pattern of results being consistent with the structural view).

Same trials. On the ‘‘different’’ trials, subjects were slower to respond when the two matrices shared the salient global pattern than when they shared the less salient global pattern. As predicted, the opposite pattern was observed for the ‘‘same’’ trials. On the ‘‘same’’ trials, subjects were significantly slower to respond correctly when the matrices had the less salient pattern than when the matrices had the salient pattern (1740 vs 1155 ms, $t(22) = 6.92$, $p < .01$). Again, there was no indication of a speed–accuracy trade-off. The error rates were 5% for the salient pattern and 6% for the less salient pattern.

Discussion

We obtained the same pattern of findings as in Experiment 1, using a different procedure. Interference effects were found when patterns globally matched (but locally mismatched), even when subjects were free to utilize repeated local identity comparisons. The results provide further support for our view that equivalence class comparisons can precede local element identity comparisons.

EXPERIMENT 3

The theoretical interpretation of Experiments 1 and 2 is that grouping of elements can precede identifying local elements. In Experiment 3, we further tested the generality of this effect by using stimuli with only three elements. The three elements were arranged in a single column, and subjects indicated whether a target column was the same as or different from a comparison column. However, because there are only three elements to be compared, it is feasible that subjects would perform local comparisons to see if the columns matched. In fact, subjects often reported adopting this strategy.

Only one global pattern was used for the standard. The pattern was ‘‘three of a kind’’ (e.g., a column of three circles). Comparison columns which were different from the standard served as the interesting test cases. If local identification played a primary role in matching, subjects could simply encode the shape form used in the standard and then search through the comparison column—responding ‘‘different’’ when a mismatch was detected and ‘‘same’’ if all three elements matched. With this strategy, only the number of local matches should affect performance (e.g., subjects should report quickly that a column of circles is different from a column of squares).

Our opportunistic account of processing predicts that the greater the global match between the standard and the comparison columns, the more difficult it will be for the subjects to determine that they are different. For example, we predict that subjects will have difficulty detecting that a column of three squares is different from a column of three triangles because both columns share the same global structure (even though the columns mismatch at every position). Quickly processing global information does not preclude local matches from being important (e.g., local and global information can be processed concurrently), and we predict, as before, that the greater the number of local matches, the more difficult it will be to classify the matrices as different.

Methods

Subjects. Twenty-four Northwestern University undergraduate students participated in the experiment for course credit.

Stimuli. Stimuli were columns consisting of three shape elements (either triangles, circles, or squares). All possible combinations of shapes and patterns were made, yielding 27 different columns. Each shape array was 5.5 by 1.5 cms on the screen (which subtended 7.8 by 2.1° of visual arc). Each shape elements was 1.5 by 1.5 cms (which subtended 2.1° of visual arc).

Design. The standard array had three shapes of the same kind (i.e., either three triangles, three circles, or three squares). For ''different'' trials, each standard array was paired with every possible array, except for itself, yielding $3 \times 26 = 78$ ''different'' trials. Each standard array was paired with itself 26 times to give $3 \times 26 = 78$ ''same'' trials.

Although global and local match were not manipulated factorially as in previous experiments, the degree of local and global match varied across trials. On ''different'' trials, there were three levels of local match. The two arrays could have 0, 1, or 2 local matches. Local matches were defined in the same fashion as in Experiment 1.

Our characterization of the grouping by similarity mechanism suggests three different levels of global match. The best match would be a comparison array where all three shape elements are the same (e.g., three triangles). In this case, both the standard and comparison arrays have the identical global structure. A slightly less compelling match would be one in which the comparison had only two elements of the same type (e.g., a triangle and two circles). In this case, the structure of the standard and comparison differ, but not radically. The greatest mismatch between the global structure of the standard and comparison would occur if the comparison consisted of three different elements (e.g., a triangle, a circle, and a square). In this case, the structures differ greatly (i.e., three of the same kind vs one of each kind).

Unfortunately, the 3×3 factorial design suggested by the three levels of local and global match is not logically possible. For example, it is impossible to have a comparison that has one local mismatch with the standard, but has the identical global structure as the standard.

Procedure. The procedure was the same as in Experiment 1 except that subjects did not receive feedback.

Results

Trials with response times less than 200 or greater than 5000 ms were discarded (these discarded trials comprised less than 1% of the total). Subjects responded ''SAME'' on 96% of the ''same'' trials and ''DIFFERENT'' on 97% of the ''different'' trials. Correct response latencies were 481 and 540 ms for the ''same'' and ''different'' trials, respectively.

Table 3 shows the averaged median correct response times for the ''different'' trials as a function of degree of global and local match. As in Experiments 1 and 2, a median correct response latency was tabulated for each subject in each condition. The entries in Table 3 are the mean of these medi-

TABLE 3
Averaged Median Correct Response Latencies and Proportion Correct for the ‘‘Different’’ Trials in Experiment 3

	Local matches		
Global pattern	0	1	2
Three of a kind	577 ± 14 (.93)		
Two of a kind	528 ± 6 (.98)	546 ± 9 (.97)	555 ± 8 (.96)
All different		518 ± 10 (.98)	

ans for each condition. A one-way ANOVA over all five conditions was statistically significant ($F(4, 92) = 4.58$, MSe $= 12876$, $p < .01$). The standard errors of the condition means are shown in Table 3. These standard errors are based on the within-subject design, that is, they do not include variability due to subject differences (e.g., subjects' grand means were subtracted from each observation). One reason cell standard errors differ is that there are an unequal number of observations per cell. For instance, each subject only observed six ‘‘different’’ trials in which the comparison column was three of a kind.

Table 3 shows the response accuracies for each ‘‘different’’ condition in parentheses. There was no indication of a speed–accuracy trade-off. In fact, error rates for the slower conditions tended to be higher.

The pattern of results provides evidence for both an opportunistic account of the matching process and the grouping by similarity mechanism. Responses should be slower as the degree of local and global match increases. Accordingly, the averaged median of each cell in Table 3 is in the predicted order. Response latencies increase as the degree of local match increases in the ‘‘two of a kind’’ global pattern condition. With no local matches, the ‘‘three of a kind’’ pattern is slower than the ‘‘two of a kind’’ pattern, which is slower than the ‘‘all different’’ pattern in the one local match condition. The probability of observing the ordering is $1/(3! * 2 * 2) < .05$. Error rates also conformed to this ordering. Although the design of the experiment is not factorial, post hoc *t*-tests and an ANOVA can be performed. To test for an effect of local matches, a one-way ANOVA was performed on the three cells having the ‘‘two of a kind’’ global pattern; $F(2, 46) = 3.54$, MSe $=$ 4623 $p < .05$. To test the effect of differing global patterns, we compared cells that differed on their global pattern, but not on their degree of local match. With no local matches, subjects were slower to respond different to the ‘‘three of a kind’’ pattern than to the ‘‘two of a kind’’ pattern ($t(23) = 2.92$, $p < .01$). With one local match, subjects were faster to respond different to the ‘‘all different’’ pattern than to the ‘‘two of a kind’’ pattern. This result was marginally significant ($t(23) = 2.01$, $p = .06$).

Discussion

Both the response time and error rate patterns support the view that global and local information are important in the matching process. If subjects first computed the identity of each element, these results would not be observed because there would be no effect of global match. Even with only three element columns of shapes and with the standard always having the same global pattern, the degree of global match affected performance. This finding is surprising because computing local matches is easy. Experiment 3 complements Experiments 1 and 2 by providing evidence for varying degrees of global match. In Experiments 1 and 2, the global patterns either matched or mismatched (with salience varying). There appears to be a similarity metric for global patterns, with more similar patterns creating more compelling matches. As in Experiments 1 and 2, the conspicuity theories of local and global processing cannot account for the results.

GENERAL DISCUSSION

Our studies show that even when conspicuity is controlled, there are still advantages in processing global structure. In our stimuli, the global pattern can only be recovered by first identifying the local elements or by forming equivalence classes of local elements. Our results show that equivalence class formation can precede local element identification. In three same–different discrimination tasks subjects were slower to judge two stimulus arrays as different when their global patterns matched than when they mismatched. This result is surprising because information about matching or mismatching global patterns was not a perfect predictor of the correct response, but local element identification was a perfect predictor. In addition to globally matching information slowing down ‘‘difference’’ judgments, it greatly enhanced the effects of local matches on such judgments compared to judgments involving stimuli with local matches but globally mismatching patterns. This interaction suggests that the process of putting our stimuli into global correspondence can begin before local elements are put into correspondence. In a final experiment, we used very simple stimuli in another same–different discrimination task. Because the stimuli consisted of just a few shapes, it was easy to perform the discrimination by comparing corresponding shapes. Nevertheless, global matches again slowed down difference judgments.

Our studies also showed local effects, in which the number of local matches slowed ‘‘different’’ responses. Again, local matches had a stronger effect on difference judgments when globally matching information was present as well. This effect was also systematically related to the salience of the matching global pattern—local matches had stronger effects when the matching global pattern was more salient (Experiments 1 and 2).

Taken as a whole, the results are consistent with the view that global match is determined by a mechanism that groups together local elements of a stimulus prior to identification of the local elements. For example, squares are grouped together, not because they are squares, but because they are similar and proximate. As noted, previous work has attributed global and local effects to differences between the conspicuity of local and global forms. Yet our findings show that differences in conspicuity are not necessary in order to demonstrate these effects. How then can the present account be reconciled with the previous work? Certainly, conspicuity is important in global and local processing, especially when ‘‘place stimuli’’ (e.g., the nested letters) are used. Lamb and Yund (1993, 1996) may present the most convincing study, in which filtering out low spatial frequencies obviates a global advantage. Our results show that conspicuity cannot be the sole factor in determining the relationship between local and global processing. Structural factors also appear to play an important role.

The results from nested letter stimuli (in which the global forms differ in conspicuity from local forms) are particularly amenable to theories that focus on conspicuity at the expense of structural relationships. Our results suggest that structural explanations may also play a vital role in perception. Pomerantz argues that nature stimuli, such as the type used here, may provide a ‘‘different window’’ into perceptual processing. We agree, and hope that more researchers consider using nature stimuli as well place stimuli.

Consistent with our approach, structural principles are realized by grouping processes in some theories of visual search (Duncan & Humphreys, 1989; Pashler, 1987). Grouping allows a visual display to be segmented into regions (i.e., equivalence classes) prior to identifying the elements forming a region. In brief, a typical visual search task involves searching for a target (e.g., an ‘‘L’’) amidst a number of distractors (e.g., many ‘‘T’’s). Subjects indicate whether the target is present or absent. Grouping distractors into equivalence classes can lessen search time by making it possible to reject an entire class of distractors at once. Placing distractors into classes effectively reduces the number objects in the display. For instance, Humphreys and Müller’s (1993) visual search model correctly predicts a quick ‘‘absent’’ response when the display consists of uniform distractors (e.g., only T’s are displayed). In such cases, all the distractors (e.g., T’s) can be grouped together (i.e., placed into one equivalence class) and quickly rejected, leaving no other objects to examine.

The above theories of visual search have been implemented in computational models. Humpreys and Müller’s (1993) model, as well as Grossberg, Ross, and Mingolla’s (1994) groups distractors based on the Gestalt principles of similarity and proximity. The grouping operations of these models is consistent with our account of grouping and lends credence to the notion that grouping can allow for stimuli to be partitioned into broad equivalence classes prior to the identification of local elements. However, these models are not directly applicable to uncovering global structure because the demands of our tasks differ from those of visual search. Instead of grouping to quickly reject multiple distractors, groups, along with their spatial relationships, are used to uncover the global pattern. The computational approaches for forming groups in visual search serve as an example of the computations sufficient for grouping for global identification.

In this work, we have not tested computational accounts of grouping. Our experiments are designed to show that equivalence class formation can precede local element identification, but they do not provide the degree of control to test various computational accounts. However, we believe our experimental design will place important constraints on computational approaches in perception, but this remains for future study.

Global and Local Processing in Other Domains

Our account of local and global processing is structural. Like theories of analogy (e.g., Gentner, 1983), our approach highlights the importance of structural principles in determining global correspondences. Therefore, our view informs theories in nonvisual domains that emphasize structural processing, such as theories of metaphor, analogy, and similarity. Our view was substantiated primarily on the basis of results from same–different discrimination tasks. Same–different tasks are well suited to exploring issues involving structural comparison in higher-level cognition. Same–different tasks involve a comparison process in which elements of perceptual stimuli (or their representations) are placed into correspondence (Medin, Goldstone, & Gentner, 1993). Such comparison processes figure prominently in accounts of analogical processing and similarity judgments (c.f., Markman & Gentner, 1993b; Medin et al., 1993). In contrast, typical local–global tasks involve identifying either the local or global form of a stimulus, as opposed to comparing two stimuli and searching for differences (e.g., Navon, 1977).[6]

A variety of models of high-level cognition assume that processing occurs in a strict local-to-global fashion. They include models of metaphor and analogy interpretation (Gentner, 1983; Falkenhainer et al., 1989; Holyoak & Thagard, 1989; Keane & Brayshaw, 1988), similarity judgments (Goldstone, 1994; Markman & Gentner, 1993a, 1993b) and the interpretation of noun–noun compounds (Wisniewski, 1996). In brief, all of these models postulate a two-stage comparison process which takes the mental representations of a pair of items and puts them into correspondence. In the first stage, all possible local correspondences are generated between similar elements in the two representations. In the next stage, local correspondences are coalesced into global correspondences which involve large sets of these elements. The global correspondences are determined by several structural con-

[6] Another potential advantage of the same-different task is that the relation between response times from same-different tasks and similarity ratings has already been explored (Podgorny & Gardner, 1979; Corter, 1987; Sergent & Takane, 1987).

straints (see Falkenhainer et al., 1989 for a detailed description of this type of algorithm).

Note that this approach to modeling high-level cognition contrasts with the general view in perception that processing is flexible (situationally dependent) and does not proceed in a strict order (i.e., either global-to-local or local-to-global). As noted in the introduction, the salience of the local and global form can enhance one type of processing versus the other, suggesting that structural processing is opportunistic. For instance, with our stimuli, it appears that global comparisons are made prior to local comparisons through equivalence class formation, but with different stimuli the opposite pattern of results may hold. Given the popular view that high-level cognition is intimately connected and derived from perception (Barsalou, 1993; Finke, 1985; Gilbert, 1991), our results suggest that the existing local-to-global models of higher level cognition are too rigid and that more flexible approaches should be favored (e.g., Hummel & Holyoak, 1997).[7] Local-to-global approaches may have endured because they account for the product of a mental comparison, without evaluating the process of comparison (however, see Goldstone & Medin, 1994, for a notable exception). For example, local-to-global algorithms that account for the output of analogical interpretation have not been examined with respect to the time course of interpretation.

Specifying a Model of Structural Comparison

Our work investigates the plausibility of establishing global (i.e., relational) correspondences prior to local correspondences. Clarifying how global and local information (or, more generally, information at varying levels of abstraction) interacts would shrink the space of possible models of comparison and alignment. The present results cast doubt on the local-to-global account of comparison. In fact, each experiment is at odds with local-to-global accounts of processing. However, evidence against a local-to-global comparison process should not be taken as evidence for global-to-local processing (a finding can be inconsistent with both accounts).

The current work also presents serious problems for global-to-local accounts of processing. In our experiments, local matches slowed subjects' ''difference'' judgments even when stimuli globally mismatched, contrary to the global-to-local view. If global structure is recovered prior to *any* local processing, it is unclear why local matches should affect subjects' performance when there is a global mismatch. Another finding that could be problematic for a global-to-local approach to comparison is that ''same'' responses were faster than ''different'' responses in Experiment 3 (the only experiment in which subjects were not biased to respond ''different'' due to the predominance of ''different'' trials). If processing was strictly global-to-local, subjects viewing identical shape arrays would first compare them

[7] Of course, unconstrained flexibility is not desirable.

at the global level. When two arrays matched at the global level, subjects would then begin comparing the local elements. Such an algorithm predicts that ‘‘same’’ responses should be slower than ‘‘different’’ responses (with the possible exception of the ‘‘three of a kind’’ condition).

Another problem with a strict global-to-local view is that it may not always be possible to access global information prior to local information. For every domain, there must be a mechanism that allows for global information to be extracted prior to local information (with our stimuli, a grouping mechanism made quick global pattern identification possible). Additionally, the local/global literature (taken as a whole) argues against both strict local-to-global and global-to-local processing by virtue of demonstrating both local and global advantages.

We hope that the work presented here will have an influence on those studying similarity and analogy (especially those concerned with constructing process models). Our results bear directly on theories of analogy and similarity by offering a window into how humans draw comparisons. Hopefully, our work will serve to strengthen links between researchers in perception and cognition and highlight the mutual relevance of each field’s findings.

SUMMARY

We show that a global advantage can occur even when the local and global form have the same conspicuity. We argue that this advantage occurs because equivalence classes of similar and proximate local elements can be constructed prior to local element identification. This is accomplished by a grouping process. We argue against strict local-to-gobal and global-to-local accounts of processing, instead we favor a more opportunistic account of processing. As our approcach and task emphasize structured comparison, our results are relevant to work in higher-level cognition.

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